

Emission of Carbonaceous Species from Biomass Burning in the Traditional Rural Cooking Stove in Bangladesh

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Abstract

Characterization of carbonaceous species from the particulate matters (PM) after combustion of seven commonly used biomass species, albizia tree (*Albizia julibrissin*), dry leaves (mahogany tree), jackfruit tree (*Artocarpus heterophyllus*), rain tree (*Samanea saman*), mahogany tree (*Swietenia mahogany*), cow dung and mango tree (*Mangifer aindica*) was done. PM samples were collected on quartz fiber filters emitted from biomass burning in a typical rural cooking stove. PM loaded filters were characterized with scanning electron microscope (SEM) for surface morphology, fourier transform infrared (FTIR) to determine the functional group of organic compounds. Black carbon (BC) and brown carbon (BrC) concentrations were determined with Aethalometer. A TOC analyzer was used to determine the total organic carbon (TOC) present in the biomass samples. The surface morphology was almost similar for all biomass burning PM samples. The average concentrations of BC and BrC were 5.85 ± 4.40 and $13.0 \pm 8.80 \mu\text{g}\cdot\text{m}^{-3}$, respectively. The emission factors of BC and BrC were 1.08 ± 0.89 and $2.35 \pm 1.67 \text{ mg}\cdot\text{g}^{-1}$, respectively. Concentration of BC was the highest in dry leaves and the lowest in mango tree. The emission factors of the determined biomass followed the sequence-dry leaves of mahogany > albizia tree > jackfruit tree > rain tree > cow dung > mahogany tree > mango tree. PM from mango tree had lower emissions compared to the other biomass species used in this study.

Keywords

Biomass Burning, Particulate Matter, Black Carbon, Brown Carbon, Total Organic Carbon

1. Introduction

Biomass burning is considered as the significant source of air pollution, which

has serious impact both on public health and climate. Solid biomass burning releases large amount of pollutants like particulate matter (PM), black carbon (BC), Organic carbon (OC), carbon monoxide (CO), formaldehyde etc. [1]. These pollutants are causing respiratory infections, pulmonary diseases, asthma and diseases of the eye. PM 2.5 can enter deep into the lung and responsible for more than 3.1 million deaths in 2010 [2] [3]. Moreover, pollutants from the household biomass burning can result in more than 1.6 million deaths per annum [4]. In addition to human health, biomass burning has adverse effects on the climate. It is considered as the most significant source of BC emissions in the atmosphere [5] especially South East Asia, which is very efficient in absorbing solar radiation [6]. In recent studies, light absorbing organic aerosol, which is known as brown carbon (BrC) [7] [8] [9] is increasingly included in climate models that can also absorb solar radiation efficiently at specific wavelengths [10] to know the carbonaceous aerosol role in global climate [11]-[16]. Previously we have reported the emissions of trace metals in black solid materials from biomass burning [17]. Whereas, no information is available for black carbon (BC) and brown carbon (BrC) emissions from biomass burning.

Bangladesh is a rapidly growing Southeast Asian country but about 80% people of the country are still living in the rural areas. Most of the cooking in rural areas of Bangladesh is done in indoor environments with very little ventilation. Almost 70% of them are using various biomass species, including rice husk, straw, cow dung, jute stick, bagasse, bamboo, dry leaves, and woods as main fuels for cooking foods [18]. Biomass burning is producing huge amount of PM, toxic gaseous pollutants (NO_x , SO_x , CO_2 , CO, VOC etc.) and heavy metals (Pb, Cu, Co and Zn etc.) [19]. Production of these pollutants depends significantly on the position of kitchen, types of fuel use, and also ventilation on indoor air quality [20]. However, very limited information is available for the characterization of biomass burning emission in Bangladesh.

Therefore, we are focusing on the BC, BrC and TOC emissions of seven commonly used biomasses in the rural cooking stove in Bangladesh. PM was collected on quartz filter and analyzed for surface morphology with scanning electron microscope (SEM), functional group of various organic compounds with fourier transform infra-red (FTIR) spectroscopy, concentrations and emission factors for BC and BrC with an aethalometer and total organic carbon (TOC) concentration with an TOC analyzer.

2. Methods and Experimental

2.1. Physical Characteristics of the Biomass Samples

Seven different biomass samples, e.g., albizia tree (*Albizia julibrissin*), dry leaves (mahogany tree), jackfruit tree (*Artocarpus heterophyllus*), rain tree (*Samanea saman*), mahogany tree (*Swietenia mahogany*), cow dung and mango tree (*Mangifer aindica*) were selected which are widely used for cooking purposes in rural and sub-rural areas in Bangladesh. Among all mahogany and jackfruit trees were

hard wood; mango, albizia and rain trees were moderately hard wood, whereas dry leaves and cow dung were very light species. All the species were collected from Barisal district (southern part of Bangladesh) during the winter season (December, 2014-February, 2015) and transported to the Department of Chemistry, University of Dhaka. The species were cut into small pieces with a length of 4 inches and dried for burning in the cooking stove.

2.2. Description of Cooking Stove

Deposition of PM by biomass burning is dependent on both types of biomass and cooking stoves [20]. Almost all the cooking stoves are made of mud (local name is “Chula”) with one or multi-channel in rural and sub-rural areas in Bangladesh. A two channel, mobile cooking stove was made with mud in the Atmospheric and Environmental Research Laboratory, Department of Chemistry, University of Dhaka where the experiments were carried out.

2.3. Particulate Matter (PM) Sample Collection

PM samples were collected from the combustion of seven biomass species. Before sampling each quartz filter (Gelman, membrane filters, 47 mm diameter) was heated at 800°C for 4 hours to remove all impurities. The one stage inline 9631, NILU filter holder (diameter 90 mm, length 70 mm) filled with quartz filters were placed about 31 cm on top of the cooking stove. About 50.0 g of each biomass species was fed into the cooking stove for burning. Deposited PM weight was calculated from the differences between PM loaded and unloaded filters. The volume of air was recorded from the difference of the initial and final Gas meter reading. The PM loaded filters were kept in a petri-disk and preserved in a desiccator to prevent moisture at controlled temperature and humidity.

2.4. Analytical Method

2.4.1. Scanning Electron Microscope (SEM)

A scanning electron microscope (SEM), (model “JEOL”, SN-JSM-6490LA, Japan) was used to characterize the surface morphology of the PM samples. Magnification range of the SEM images was $\times 1000$ - $\times 50,000$. The expected particle size of the PM in quartz filters was 1 μm - 100 μm .

2.4.2. FTIR Analysis

A fourier transform infrared spectrometer (model “IR Prestige 21”, SN-A21004902879LP, Japan) was used to study the functional group of the PM particles. A very thin layer of PM was taken from the quartz filter with a spoon and mixed properly with potassium bromide (KBr) finely to remove scattering effects from large crystals. A mechanical press is used to press the resultant powder to a translucent pellet through which the beam of the spectrometer can pass. IR spectroscopy is often used to identify structures because functional groups give rise to characteristic bands, both in terms of intensity and position (frequency).

2.4.3. Aethalometer Data Analysis

The soot scan™ model OT21 transmissometer (Magee scientific transmissometer OT21; USA) bench top analyzer was used to measure both BC and BrC from different biomass burning emissions. This aethalometer contains a two wavelength light source: 1) 880 nm providing the quantitative measurement of BC (near IR range), and 2) 370 nm for measurement of BrC (UV visible range). The light was passed through the PM loaded filters that decrease the transmission of light, and the decreasing of transmission leads to the increasing attenuation [21]. Transmission of light through the sample-laden filter is measured and the attenuation (ATN) coefficient is calculated from the rate of attenuation change with time [22].

1) Attenuation Measurement

BC mass concentrations were estimated by an aethalometer from the rate of change of light transmission through a filter [23]. As the transmission decreases attenuation increases. Attenuation factor for both BC and BrC were determined in PM loaded filters by using the following equations [24]:

$$ATN = 100 \times \ln(\text{blank transmission/sample transmission}) \quad (1)$$

where ATN is the attenuation factor. ATN_1 is the attenuation factor before heating of the PM loaded filters and ATN_2 is the attenuation factor after heating the sampled filters at 340°C for 3 hours for both blank and sample filters at both wavelengths in aethalometer (IR reading at 880 nm and UV reading at 370 nm).

2) BC and BrC Emission Measurement

The density of BC and BrC were calculated by using ATN value at 880 nm and 370 nm, respectively with the following equation:

$$\delta = (ATN_1 - ATN_2) / \sigma_{ATN} \quad (2)$$

where δ is the carbon density in $\mu\text{g}\cdot\text{cm}^{-2}$ and σ_{ATN} is the specific attenuation co-efficient, which is $16.6 \text{ cm}^2\cdot\mu\text{g}^{-1}$. The concentration of BC and BrC were calculated from the density of BC and BrC by using the following equation:

$$C_d = (\delta \times A) / V_{ms} \quad (3)$$

where C_d is the measured carbon concentration ($\mu\text{g}\cdot\text{m}^{-3}$), A is the collection area of the filter (14.5 cm^2) and V_{ms} = volume of air during sampling from the dry gas meter.

3) Emission Factor Estimation of BC and BrC

Residential biomass burning emission factors is very important as they provide a measure of the amount of pollutants emitted to the atmosphere per mass of fuel combusted. The emission of BC and BrC were calculated from the concentration of BC and BrC by using the following equation:

$$E = (Fc \times Cd \times 100\%) / \%CO_2 \quad (4)$$

where E is black carbon emission ($\mu\text{g}\cdot\text{j}^{-1}$) and Fc is Carbon based F factor ($\text{m}^3\cdot\text{j}^{-1}$) which is $4.84 \times 10^{-6} \text{ m}^3\cdot\text{j}^{-1}$. The carbon dioxide percentage of the sampling area was 0.031. The emission factors for seven biomasses were calculated using the

following equation:

$$EF = (E \times GCV) / 1000 \quad (5)$$

EF is carbon emission factor ($\text{mg}\cdot\text{g}^{-1}$), E is black carbon emission ($\mu\text{g}\cdot\text{j}^{-1}$) and GCV = gross calorific value of fuel.

2.4.4. Total Organic Carbon (TOC) Determination

A TOC analyzer (model "TOC-V CPN"; SN-H51304500919AE, Japan) was used to determine the total organic carbon present in the PM after burning of each biomass species. The filter samples were dissolved in a 15 mL de-ionized water in reagent bottles. After that the reagent bottles containing samples were placed in a shaking bath for one hour and then sonicated in an ultrasonic bath for 30 minutes. Finally, all the solutions were carried for the determination of total organic carbon (TOC) concentration.

3. Results and Discussion

3.1. Overview of the Results

This study involves emission of carbonaceous species from seven biomasses in a typical rural cooking stove made of mud. Albizia tree, dry leaves of mahogany, jackfruit tree, rain tree, mahogany, cow dung and mango tree were used as biomasses. Particulate matters (PM) were collected on quartz filters with an SPM sampler (TUV, Austria) on about 31 cm top of the cooking stove. Surface morphology of the PM was studied with SEM and both coarse and fine particles were obtained for seven biomass species. Functional group of various organic compounds was analyzed with FTIR and they are quite similar to each other. The concentrations and emission factor for BC and BrC were analyzed using a two wavelength aethalometer after burning of each biomass separately in the cooking stove. BrC concentrations and emission factor was higher than BC for all biomass species. The highest amount of BC content found in the dry leaf of mahogany tree and the lowest amount of BC found in the mango tree. The highest amount of BrC content found in the albizia tree and lowest amount in the mango tree. TOC in PM was analyzed by TOC analyzer for individual biomass species. Among all biomasses albizia contains the highest amount of TOC, whereas mango shows the lowest.

3.2. Surface Characterization with Scanning Electron Microscope (SEM)

Scanning electron microscope (SEM) was used to characterize the surface morphology of the PM obtained from seven biomass species (albizia, dry leaves, jackfruit, rain, mahogany, cow dung and mango) after burning in the cooking stove. Two types of particle (coarse and fine) were obtained. Coarse particles (particles having diameter $> 2.5 \mu\text{m}$) were found for cow dung, dry leaves, mahogany and mango; whereas, fine particles were found (particles having diameter $< 2.5 \mu\text{m}$) for albizia, jackfruit and rain. Salam *et al.* reported that the smoke

deposits surfaces may contain dust, sulfate, nitrate and also oxides of different metals dominating by carbonaceous species [25].

3.3. Functional Group Identification with Fourier Transform Infrared (FTIR) Spectroscopy

IR spectrum was taken of the PM of seven biomasses. Individual spectrum was obtained for the respective functional groups of various organic compounds for seven different biomass samples which have shown below (Table 1).

3.4. Concentration of Black Carbon (BC) and Brown Carbon (BrC)

3.4.1. Black Carbon (BC)

The BC and BrC concentrations were varied among the biomasses. The BrC concentrations were much higher than that of BC for all the biomasses (Figure 1). The average concentration of BC in all biomasses was $5.85 \mu\text{g}\cdot\text{m}^{-3}$. The BC concentration was highest in the dry leaves of mahogany tree and lowest in the mango tree. The BC concentration of seven biomass species was as follows-dry leaves > albizia > jackfruit > rain > cow dung > mahogany > mango. BC concentration in the dry leaves of mahogany tree was almost 13 times higher than mango tree

3.4.2. Brown Carbon (BrC)

The average concentration of BrC was $13.0 \mu\text{g}\cdot\text{m}^{-3}$. The BrC concentration was highest in albizia tree and lowest in mango tree. The concentration of BrC in all biomasses followed the sequence-albizia > dry leaves > jackfruit > rain tree > cow dung > mahogany tree > mango tree (Figure 1). BrC concentration in albizia tree was almost 12 times higher than mango tree.

The BrC concentration compared to BC was 2.50 times higher in albizia tree, 1.50 times higher in dry leaves of mahogany tree, 2.75 times higher in Jackfruit tree, 2.50 times higher in rain tree, 2.0 times higher in cow dung, 3.00 times higher in mahogany tree and 2.75 times higher in mango tree.

3.5. Emission Factor of Black Carbon (BC) and Brown Carbon (BrC)

3.5.1. Black Carbon (BC)

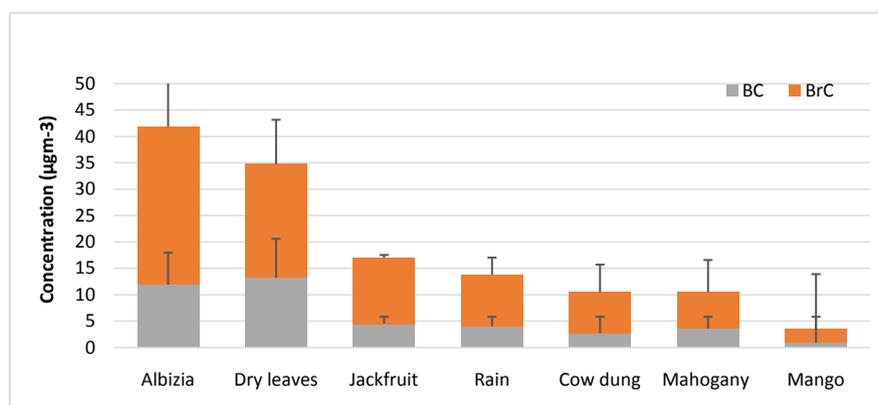
The average of emission factor for BC of all biomasses in this study was $1.09 \text{mg}\cdot\text{g}^{-1}$. The emission factors for brown carbon were always higher than that of black carbon for seven biomasses. BC emission factor was highest in the dry leaves of mahogany tree and lowest in the mango tree. The order of BC emission factor was as follows-dry leaves > albizia > jackfruit > rain > cow dung > mahogany > mango (Figure 2).

3.5.2. Brown Carbon (BrC)

The average emission factor of BrC was $2.35 \text{mg}\cdot\text{g}^{-1}$. BrC emission factor was highest in albizia tree and lowest in mango tree. The BrC emission factor followed the sequence: albizia > dry leaves > jackfruit > rain > cow dung > mahogany > mango (Figure 2).

Table 1. Characteristic functional group of the individual biomass burning emission with FTIR styles (Table caption is indispensable).

Biomasses	Functional group
Albizia	--OH (Alcoholic-H bonded, 3446 cm^{-1}), --COOH (2363 cm^{-1}), 1° and 2° Amine (--NH ₂ , 1540 cm^{-1}), R-N=O (1520 cm^{-1}), Amine (C-N, 1340 cm^{-1}), Cl ⁻ (790 cm^{-1}), F ⁻ , I ⁻ (486 cm^{-1}).
Dry leaves	--OH (Alcoholic-H bonded, 3443 cm^{-1}), --CHO (2933 cm^{-1}), --C-H (2881 cm^{-1}), --COOH (2372 cm^{-1}), --CO-NH ₂ (1640 cm^{-1}), 1° and 2° Amine (--NH ₂ , 1549 cm^{-1}), R-N=O (1510 cm^{-1}), Amines (C-N, 1370 cm^{-1}), S=O (1124 cm^{-1}), Cl ⁻ (811 cm^{-1}), Br ⁻ , I ⁻ (482 cm^{-1})
Jackfruit	--OH (Alcoholic-H bonded, 3446 cm^{-1}), --CHO (2929 cm^{-1}), --C-H (2860 cm^{-1}), --COOH (2360 cm^{-1}), --CO-NH ₂ (1647 cm^{-1}), 1° and 2° Amine (--NH ₂ , 1540 cm^{-1}), R-N=O (1510 cm^{-1}), Aromatic alkenes (1439 cm^{-1}), F ⁻ (1390 cm^{-1}), C-N (Amines, 1340 cm^{-1}), S=O (1320 cm^{-1}), Cl ⁻ (780 cm^{-1}), I ⁻ (484 cm^{-1}).
Rain	--OH (Alcoholic-H bonded, 3451 cm^{-1}), --CHO (2901 cm^{-1}), --C-H (2840 cm^{-1}), --COOH (2362 cm^{-1}), --CO-NH ₂ (1648 cm^{-1}), = Aromatic alkenes (1410 cm^{-1}), S=O (1075 cm^{-1}), Cl ⁻ (769 cm^{-1}), I ⁻ , Br ⁻ (480 cm^{-1})
Mahogany	--OH (Alcoholic-H bonded, 3456 cm^{-1}), --CHO (2929 cm^{-1}), --C-H (2840 cm^{-1}), --COOH (2364 cm^{-1}), --CO-NH ₂ (1630 cm^{-1}), 1° & 2° Amine (--NH ₂ , 1540 cm^{-1}), = Aromatic alkenes (1390 cm^{-1}), C-N (Amines, 1340 cm^{-1}), S=O (1124 cm^{-1}), Cl ⁻ (780 cm^{-1}), Br ⁻ , I ⁻ (486 cm^{-1}).
Cow dung	--OH (Alcoholic-H bonded, 3438 cm^{-1}), --CHO (2920 cm^{-1}), --C-H (2840 cm^{-1}), S-H (mercaptans, 2525 cm^{-1}) --COOH (2373 cm^{-1}), --CO-NH ₂ (1629 cm^{-1}), 1° and 2° Amine (--NH ₂ , 1550 cm^{-1}), F ⁻ (1432 cm^{-1}), S=O (1125 cm^{-1}), Cl ⁻ (725 cm^{-1}), Br ⁻ , I ⁻ (486 cm^{-1}).
Mango	--OH (Alcoholic-H bonded), --CHO (2910 cm^{-1}), --C-H (2850 cm^{-1}), --COOH (2367 cm^{-1}), F ⁻ (1400 cm^{-1}), S=O (1126 cm^{-1}), Cl ⁻ (781 cm^{-1}), Br ⁻ , I ⁻ (480 cm^{-1})

**Figure 1.** Comparison between BC and BrC concentrations in different biomass species.

The BrC emission factor compared to BC emission factor was 2.50 times greater in albizia tree, 1.65 times greater in dry leaves of mahogany tree, 2.75 times greater in jackfruit tree, 2.50 times greater in rain tree, 1.78 times greater in cow dung, 2.00 times greater in mahogany tree and 2.20 times greater in mango tree. The significance of the emission factor is that, if we multiply the emission factor of each biomass sample with a fixed amount of the respective biomass then we can find out the emission of carbon content (BC and BrC) for that amount of biomass.

3.6. Total Organic Carbon (TOC) Concentration

Total organic carbon (TOC) in albizia tree, dry leaves (mahogany tree), jackfruit tree, rain tree, cow dung, mahogany tree and mango tree was 5.07, 3.92, 3.51,

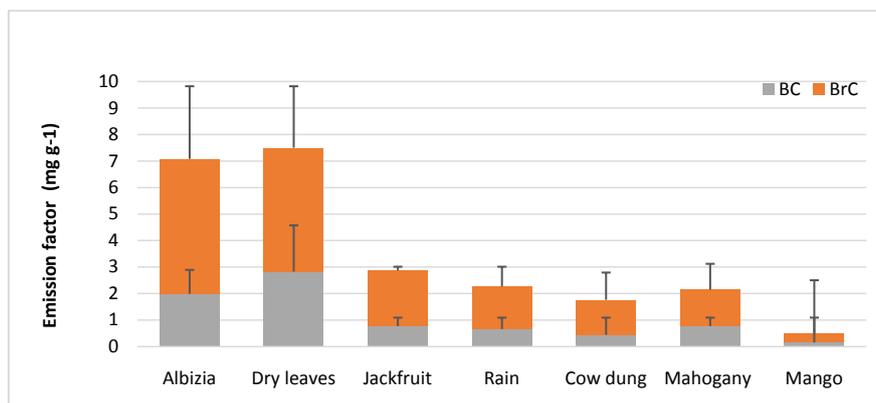


Figure 2. Comparison between BC and BrC emission factor in different biomass species.

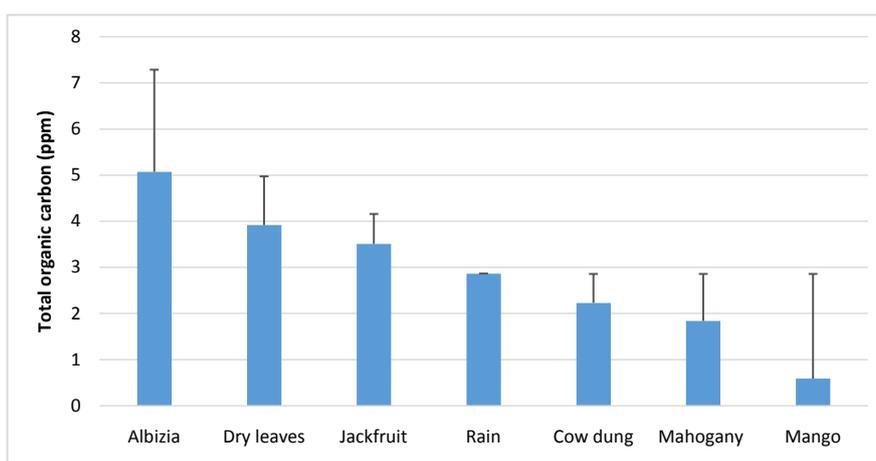


Figure 3. Total organic carbon (TOC) present in biomass sample.

2.86, 2.23, 1.83 and 0.58 ppm, respectively (**Figure 3**). The average TOC present in seven biomass samples was 2.86 ppm. The concentration of TOC was highest in albizia tree, whereas least in mango tree. In albizia tree the amount of TOC was 8.62 times higher than mango tree.

4. Conclusions

The study involves the carbonaceous species characterization of PM of seven biomasses (albizia tree, dry leaves of mahogany, jackfruit tree, rain tree, mahogany tree, cow dung and mango tree) after burning in a controlled cooking stove. The following conclusions are drawn from the present investigation:

- Coarse particles and fine particles were obtained from SEM. Particle sizes for cow dung, dry leaves, mahogany and mango were coarse in size; whereas, albizia, rain and jackfruit trees were fine in size.
- FTIR was used to analyze the functional group of various organic compounds. The functional groups of seven biomasses were almost similar.
- For all biomass species, concentration and emission factors for BrC were higher than BC.

- Dry leaves contain the highest concentration of BC, whereas mango contains the lowest. On the other hand, albizia contains the maximum concentration of BrC, whereas mango contains the minimum.
- TOC concentration was the highest for albizia and the lowest for mango.
- Mango tree emitted the lowest amount of BC, BrC and TOC that signifies that it has the least hazardous impact on the environment.

Therefore, we should be very much careful to select biomass species as an alternative to fossil fuel for cooking. For a better environmental aspect, we should use low BC and BrC containing biomasses like mango tree for cooking and other burning purposes.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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