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Studies of Gas Emissions and Performance of Stoves Using Biomass Char-Briquettes

Tessembou Biaye, Philippe Bernard Himbane and Lat Grand Ndiaye

Laboratory of Chemistry and Physics of Materials, Assane Seck University of Ziguinchor, Senegal, BP 523 Ziguinchor, Senegal

Abstract: In this article, we evaluated the energy performance parameters and gas emissions to identify which of the stoves studied performs best, and the biomass char briquettes with less emission. Biomass char briquettes from peanut shells, cashew nut shells, and corn cobs were produced using wheat flour as a binder. The binder rate was set at 9% and 10%. Based on the energy performance parameters, it was highlighted that the char briquette from corn cob with 9% binder (Char_CC_9%) has the best energy performance, followed by the char briquette from peanut shells with 9% binder (Char_PNS_9%), and lastly, the char briquette from cashew nut shells with 10% binder (Char_CNS_10%). The average energy efficiency of the "jambar" stove was 15.68%, while that of the "Malgache" stove was 12.41 %. The average specific fuel consumption of the "jambar" stove was 0.12 kg of fuel per kilogram of water while that of the "Malgache" stove was 0.15 kg of fuel per kilogram of water. In terms of gaseous emissions, CO (carbon monoxide) concentrations were very high for char briquettes from corn cobs, with a CO emission factor of 0.40 g/min and NO_x emission factor of 9.79 mg/min. For char briquettes from cashew nut shells, CO and NO_x emission factors were respectively 0.30 g/min and 5.32 mg/min. The lowest average concentrations were obtained with char briquettes from peanut shells with a CO emission factor of 0.25 g/min and NO_x 3.98 mg/min.

Key words: Biomass char briquette, stoves, energy performance, emission factors.

1. Introduction

The study of charcoal and firewood combustion, as well as that of biomass charcoal briquettes in domestic households, requires particular attention to energy yields and pollutant emissions.

The consumption of coal and wood-based fuels for cooking and heating is a major source of GHGs (greenhouse gases) and air pollutants such as particulate matter with a diameter less than 2.5 µm ($PM_{2.5}$), CO (carbon monoxide), NO_x (nitrogen oxides), black carbon and SO_2 (sulfur oxides) [1]. Gas and particulate emissions from domestic biomass stoves affect billions of lives, and millions of people suffer from life-threatening illnesses linked to these emissions [2]. Due to their household tasks, women and children are the most affected by the effects of incomplete combustion [3, 4].

As a result, there are several thousand premature deaths worldwide each year [5]. Climate change can also be attributed to indoor air pollution, most of which is associated with biomass combustion [3, 6, 7]. Biomass char briquettes produced as a substitute for firewood and charcoal must also attract the attention of producers in terms of energy performance and pollutant emissions. For this reason, this study is undertaken. In many developing countries, traditional stoves are often used as a reference to compare the performance of improved cookers [8].

This paper focuses on the study of pollutant emissions and the performance of cookers using biomass charcoal briquettes.

2. Materials and Methods

2.1 Biomass Fuels for Char Briquettes Production

The biomasses used in this work are derived from agricultural waste. We chose these biomasses because of their availability, their energy content, and the place

Corresponding author: Tessembou Biaye, Ph.D., research fields: science of materials, biomass and energy.

they occupy now in the circular economy cycles of product valorization. The biomasses were collected from different locations. CNSs (cashew nut shells) were collected from the SCPL Company located in Ziguinchor, Senegal, which uses the by-products of cashew nut processing to produce syngas using gasification technology. The PNSs (peanut shells) used in this work were collected in the commune of Diouloulou, Ziguinchor region, Senegal. CCs (corn cobs) were collected from the village of Djibonker, Ziguinchor region, Senegal. To our knowledge, this is a waste that has not yet been used for domestic fuel production, which justifies its choice. Fig. 1 shows images of the different biomass samples used to make charcoal briquettes in this work.

The chars from this biomass were obtained by conducting carbonization in a local barrel kiln as indicated in Fig. 2.

2.2 Coal Briquette Production

Two formulation types of biomass char briquettes were obtained. The first formulation contains 90% of biomass char fines and 10% of binder as a percentage of dry mass. The second formulation contains 91% of biomass char fines and 9% of binder as a percentage of dry mass.

Based on these two formulation types, six biomass char briquettes were obtained using a rotor press machine. The biomass char briquettes and their coding are given in Table 1.

Fig. 3 shows a photo of the biomass char briquettes and the rotor press used to densify the biomass char.

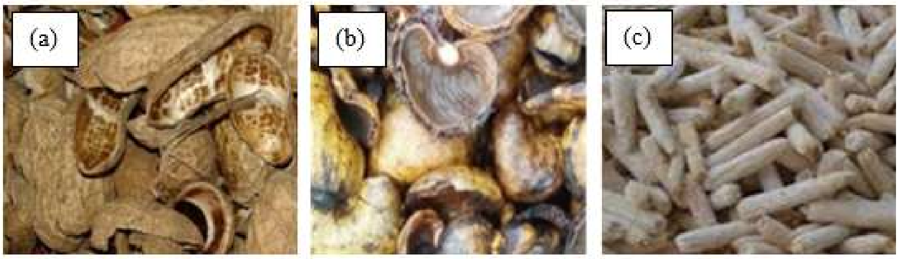

Fig. 1 Images of peanut shells (a), cashew nut shells (b), and corn cobs (c).

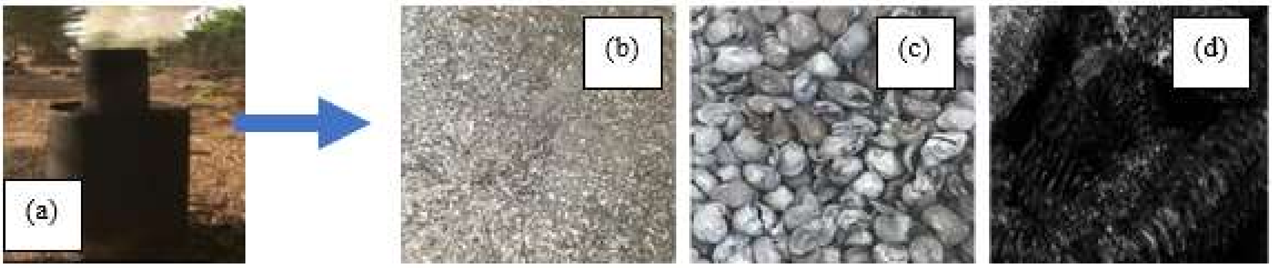

Fig. 2 Carbonization in a local barrel (a) and images of peanut shells char (b), cashew nut shells char (c), and corn cobs char (d).

Table 1 Composition of the biomass char briquettes.

Samples	Raw materials	Binder (%)	Char fines (%)	Coding
B1	Peanut shells	9	91	Char_PNS_9%
B2	Cashew nuts	9	91	Char_CNS_9%
B3	Corn cobs	9	91	Char_CC_9%
B4	Peanut shells	10	90	Char_PNS_10%
B5	Cashew nuts	10	90	Char_CNS_10%
B6	Corn cobs	10	90	Char_CC_10%

Fig. 3 Images of the rotor press machine and some biomass char briquettes produced.

2.3 Characterization of Biomass Char Briquettes

In this part, biomass char briquettes were characterized. Proximate analysis was performed and the ultimate analysis and the calorific value were determined by empirical formula. For proximate analysis, ashes content (ash) and the VM (volatile matter) content were determined, according to NF EN 1860-2 standard, by using a muffle furnace. The FC (fixed carbon) was obtained by difference. Carbon content (C), hydrogen content (H) and oxygen content (O) were estimated using the correlations proposed by Daya Ram Nhuchhen [8]. These following correlations are indicated as:

$$C\ (\%) = -35.9972 + 1.3269 \times FC + 0.7698 \times VM + 0.3250 \times Ash \quad (1)$$

$$H\ (\%) = 55.3678 - 0.5319 \times FC - 0.4830 \times VM - 0.5600 \times Ash \quad (2)$$

$$O\ (\%) = 223.6805 - 2.2296 \times FC - 1.7226 \times VM - 2.2463 \times Ash \quad (3)$$

Knowing the formula linking the elementary constituents of the biomass and its ash content, on a dry basis, we then deduced the value of the nitrogen content using the equation below:

$$N(\%) = 100 - (C + H + O + Ash) \quad (4)$$

In this study, we used the Vondracek formula to predict the HHV (higher heating value) of the various samples. This formula is defined as follows:

$$\text{HHV (kcal/kg)} = 85 \times C\% + 270 \times H\% + 25 \times S\% - 27 \times O\% \quad (5)$$

The LHV (lower heating value) was deduced from the HHV value using the formula opposite:

$$\text{LHV(kJ/kg)} = \text{HHV (kJ/kg)} - 6 \times (9 \times H + E) \quad (6)$$

where E is the moisture content of the sample in wet basis.

2.4 Determination of Energy Performance Parameters

To study the energy performance of the two selected stoves, a WBT (water boiling test) was performed. This is a simple, rapid simulation of the stages involved in cooking meals; this standard method, based on the boiling of water, is used to assess the energy performance of a domestic solid fuel stove [9]. In this work, water is used to simulate mixtures of water and food. We worked on the high-power phase, which involves bringing water to the boil as quickly as possible. To achieve this, an aluminum pot of 8 cm in diameter was filled with 5 L of water at ambient temperature (see Fig. 4).

For each test, a mass of 1 kg of biomass char briquettes is used. The bed of biomass char briquettes is lit using a blowtorch. Once the bed of biomass char briquette has sufficiently embers and glows, the pot containing the water is placed on the stove and the temperatures of the water are recorded every 5 min. The temperature recordings were made using an Arduino system connected to MAX6675 temperature sensors developed as part of Diedhiou's dissertation work [10].

For characterizing the energy performance of the two selected stoves, we focused on five parameters mainly used to characterize the energy performance of a stove. These parameters are:

- thermal efficiency;
- firepower;

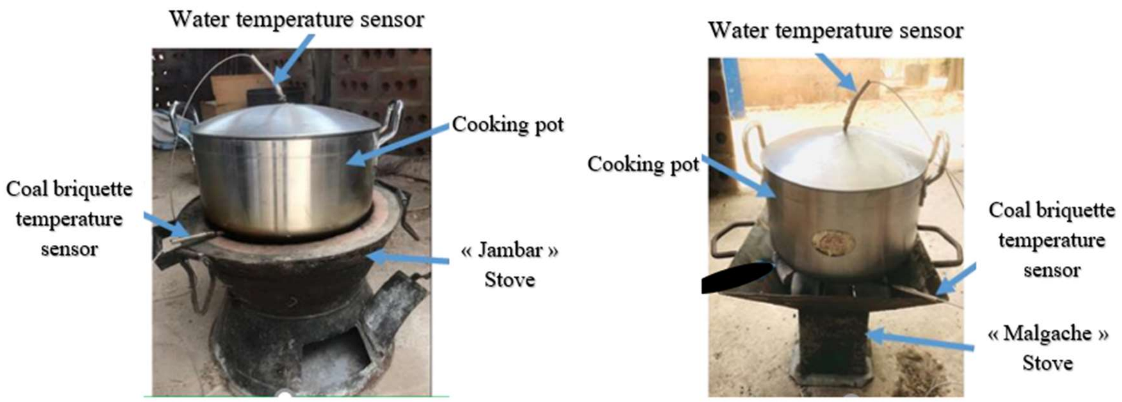

Fig. 4 Energy performance tests with both stoves.

- cooking power;
- specific fuel consumption;
- and the SBT (specific boiling time).

2.4.1 Thermal Efficiency

It expresses the capacity of the stove to restore the energy contained in the mass of fuel consumed. It is the ratio between the useful energy supplied and the fuel energy used. It is expressed as follows:

$$\eta_{th}\ (\%) = \frac{m_{w,i} \times C_{p,w}\left(T_{w,f} - T_{w,i}\right) + \left(m_{w,i} - m_{w,f}\right) \times L_{vap}}{m \times LHV} \times 100 \quad (7)$$

$C_{p,w}$ is the specific heat capacity of water: 4.18 kJ·kg^{-1}·K^{-1};

$m_{w,i}$ is the initial mass of water in the cooking vessel, in kg;

$m_{w,f}$ is the final mass of water in the cooking vessel, in kg;

$T_{w,i}$ is the initial temperature of the water in the cooking vessel, in °C;

$T_{w,f}$ is the local boiling temperature or final temperature of the water in the cooking pot, in °C;

L_v, is the latent heat of vaporization of water at the local boiling point, in kJ/kg;

m is the mass of the input fuel in kg and LHV is the lower calorific value of the fuel as burned in kJ/kg.

2.4.2 Firepower or Raw Power

Firepower is defined as the thermal energy released by the combustion of the fuel over a given time.

$$P_f(\mathrm{kW}) = \frac{m_c \times \mathrm{LHV}}{\Delta t} \quad (8)$$

m_c is the mass of fuel consumed in kg, LHV is the lower calorific value in kJ/kg, and Δt is the duration over which this power is calculated in s.

2.4.3 Cooking Power or Useful Power

The useful power is the thermal energy transferred to the mass of water in the pot over a given time. It is calculated as follows:

$$P_C(kW) = \frac{m_{w,i} \times C_{p,w}\left(T_{w,f} - T_{w,i}\right) + \left(m_{w,i} - m_{w,f}\right) \times L_{vap}}{\Delta t} = \frac{Q_f}{\Delta t} \quad (9)$$

where Q_f is the useful energy supplied in kJ and Δt is the duration of the test phase in s.

2.4.4 Specific Fuel Consumption

It represents the quantity of fuel needed to heat one liter or one kilogram of water from 0 °C to 100 °C. It is determined using the following equation.

$$SFC\left(kg_f/kg_w\right) = \frac{m_c \times (1 - E)}{m_{w,i}} \times \frac{100}{100 - T_{w,i}} \quad (10)$$

where m_c is the mass of fuel consumed, E is the moisture content of the fuel, $m_{w,i}$ is the initial mass of water and $T_{w,i}$ is the initial temperature of the water.

2.4.5 The SBT

This performance parameter measures the time required to raise a liter of water from 0 °C to 100 °C. It is therefore a factor characterizing the speed of a cooker.

It is expressed in min/kg$_w$ and is determined using the formula below:

$$SBT\ (\mathrm{min/kg_w}) = \frac{TE}{m_{w,i}} \times \frac{100}{100 - T_{w,i}} \tag{11}$$

where TE is the boiling time, $m_{w,i}$ the initial mass of water and $T_{w,i}$ the initial temperature of the water.

2.5 Measuring Gas Emissions and Calculating Emission Factors

To measure gas emissions during the combustion of the biomass char briquettes, we need a hood allowing us to extract all the fumes released. However, the hood was not available, and accordingly, to our situation, we adapted the bench using a hot air generator [11] as an extraction hood. The hot air generator, as designed, has a vacuum that enables fumes to be drawn through a chimney of 576 cm long and 15 cm in diameter [11].

For emissions tests, three biomass char briquettes were selected based on the energy performance parameters. A mass of 600 g of the selected biomass char briquettes is used for each test. The bed of biomass char briquettes is placed in a "Malgache" stove in the combustion chamber of the hot air generator (see Fig. 5) and lit with a blowtorch. Once the bed of biomass char briquettes has produced sufficient embers, the combustion chamber door is closed, and gas emissions are measured. Emitted gases are measured using a Rasi700 Biogas analyzer connected via a sampling probe to the hot air generator chimney. With a sampling rate of 1 L/min, gases were measured by intervals of 1 min. Measurement data were interfaced with the MRU4win software via Bluetooth to centralize them directly on the computer.

The image of the hot air generator used as an extraction hood is shown in Fig. 5. In the same figure we show also the images of the combustion chamber and the data centralization machine.

To calculate emission factors, data from the Rasi700 Biogas analyzer were used and processed. We focused on CO and NO_x emissions.

The quantity emitted and the emission factors for each of these two gaseous components were determined as follows:

$$X\ (g) = \sum_{i=0}^{n} V_{f,i} \frac{X_{ppm,i} \times M_X}{10^6 \times V_{m,i}} \tag{12}$$

$$V_{f,i}(L) = \frac{1000}{3600} \times \Delta t \times Q \tag{13}$$

$$Q(m^3/h) = 3600 \times v \times S \tag{14}$$

$$X\ (g/kg) = \frac{X\ (g)}{M_c} \tag{15}$$

$$X\ (g/min) = \frac{X\ (g)}{t} \tag{16}$$

$$X\ (g/MJ) = \frac{X\ (g)}{M_c \times PCI} \tag{17}$$

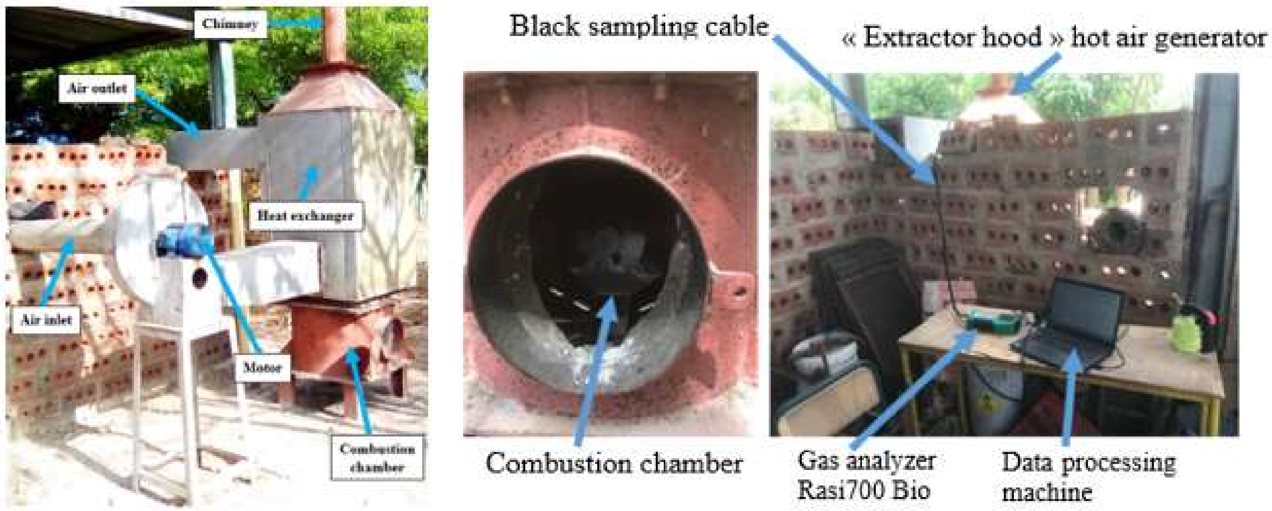

Fig. 5 Images of the hot air generator, of the combustion chamber and the data centralization machine.

where:

X represents the emitted gas, V

$V_{f,i}$, is the volume of gas collected over the time step, $X_{ppm,i}$ is the volumetric concentration in parts per million in the cooled dry gas per time step,

M_X is the molar mass (g/mol) of the gas,

$V_{m,i}$ is the molar volume of the emitted gases, which are assimilated to ideal gas (22.4 L/mol at standard temperature and pressure conditions, calculated at the smoke sampling temperature at each time step), Q is the gas volume extraction flow rate during the relevant time step,

Δt is the measurement step in s (60 s in this case) and n is the number of measurement points (around 131 s, or 2 h 10 min),

M_c is the mass of dry fuel consumed in kg,

t is the test duration in minutes (around 130 min),

LHV is the lower calorific value of the fuel in kg/MJ,

v is the average smoke velocity in the chimney and,

S is the chimney cross-section.

3. Results and Discussions

3.1 Characterization of the Samples

The results of the immediate, elementary analyses and that of the calorific value of the different samples studied are recorded in Table 2.

The physico-chemical characterization results clearly highlight the differences in physico-chemical properties between biomass char briquettes. All biomass char briquettes are predominantly composed of the element carbon. The fixed carbon content in these samples is over 60%, which is ideal for a quality biomass char briquette as stipulated in standard NF EN 1860-2. We also note the slightly elevated ash content of some biomass char briquettes. For a quality biomass char briquette, the ash content may not be above 18%.

The biomass char briquettes had LHVs ranging from 24.95 to 26.61 MJ/kg. These values are similar to those obtained experimentally by Himbane et al. [12].

3.2 Energy Performance

Energy performance parameters are summarized in Table 3. It is shown that thermal efficiency varied between 11.36% and 23.71% for the "jambar" stove and between 10.41% and 15.44% for "Malgache" stove.

Thermal efficiency differs from one biomass char briquette to another. Among the biomass char briquettes, the average thermal efficiency was 15.68% for the "jambar" stove and 12.41% for the "Malgache" stove. For the "jambar" stove, this corresponds, to a measurable improvement over the baseline reference ("Malgache" stove) on the performance levels associated with the water boiling test for high-power thermal efficiency [13, 14]. We note that the thermal efficiency is higher at lower binder contents for both char briquettes from peanut shells and corn cobs. We also remarked that char briquettes, with low binder content, burn more slowly

Table 2 Elementary and immediate analyses of the char-briquettes.

Samples	Immediate analysis (%)^s				Elemental analysis (%)^s				Calorific value (MJ/kg)^s	
	M^b	VM	Ash	FC	C	H	N	O	HHV	LHV
Char_PNS_9%	9.66	11.32	18.67	70.01	71.68	2.21	1.29	6.15	27.26	26.52
Char_CNS_9%	10.13	19.62	15.50	64.88	70.23	2.70	1.16	10.41	26.82	25.96
Char_CC_9%	9.72	9.99	19.18	70.84	71.92	2.13	1.32	5.46	27.33	26.61
Char_PNS_10%	6.97	13.47	20.02	66.51	69.13	2.27	1.36	7.22	26.31	25.62
Char_CNS_10%	7.86	18.13	15.54	66.33	71.02	2.63	1.16	9.65	27.11	26.31
Char_CC_10%	7.20	20.90	17.65	61.46	67.37	2.70	1.26	11.02	25.74	24.95

^{s}: expressed as dry basis; ^{b}: expressed in wet basis.

Table 3 Energy performance of biomass char briquettes with "jambar" and "Malgache" stoves.

Stoves	Biomass char briquettes	*Pc* (kW)	η_{th} (%)	SBT (min/kg$_w$)	SFC (kg$_c$/kg$_w$)	P_f (kW)
"Jambar" stove	Char_PNS_9%	0.58	11.95	12.89	0.14	4.83
	Char_CNS_9%	0.55	17.84	13.48	0.10	3.08
	Char_CC_9%	0.76	16.67	10.00	0.10	4.53
	Char_PNS_10%	0.49	11.36	15.36	0.16	4.30
	Char_CNS_10%	0.57	23.71	14.16	0.08	2.41
	Char_CC_10%	0.64	12.54	12.16	0.15	5.11
"Malgache" stove	Char_PNS_9%	0.84	10.62	8.88	0.16	7.91
	Char_CNS_9%	0.51	11.97	14.61	0.15	4.28
	Char_CC_9%	0.76	15.44	10.85	0.11	4.53
	Char_PNS_10%	0.62	10.41	11.89	0.17	5.92
	Char_CNS_10%	0.57	14.28	12.82	0.12	4.01
	Char_CC_10%	0.60	11.75	13.08	0.16	5.11

than those with high binder content, especially for char briquettes from peanut shells and corn cobs. The reason for this could be the higher volatile matter content of char briquettes with high binder content.

We found, for char briquettes from cashew nut shells, the thermal efficiency is higher at the high binder content level probably due to the higher volatile matter content at the high level of binder content (10%).

The decrease in thermal efficiency with increase of binder content was also observed by Himbane et al. [12] when using char briquettes from peanut shells in a "jambar" stove.

Regarding SBT, we found that char briquettes with 9% binder, excepted char briquettes from cashew nut shells during combustion in "Malgache" stove, gave the best SBT. Whatever the stove used, the best performances were achieved by char briquettes from corn cobs. Specific fuel consumption varied from 0.08 to 0.16 kg$_f$/kg$_w$ for "jambar" stove and from 0.11 to 0.17 kg$_f$/kg$_w$ for "Malgache" stove. In the case of the "jambar" stove, char briquettes from cashew nut shells with a high binder content show the lower specific fuel consumption, while char briquettes from corn cobs with a low binder content show the lower specific fuel consumption in the case of the "Malgache" stove. In "Malgache" stove, the highest firepower was obtained by char briquettes from peanut shells at low binder content, while in "jambar" stove the highest firepower was obtained by char briquettes from corn cobs at high binder content.

3.3 Char Briquettes Emission's Characterization

We chose the char briquettes with the best energy performance basing on the five parameters summarized in Table 3. Table 4 summarizes the grading results for the different biomass char briquettes.

We remind that the choice is made by type of biomass char briquette and that a biomass char briquette would present the best performance if its overall average rank was lower.

Analysis of Table 4 shows that whatever the type of stove used, the char briquettes made from corn cobs with 9% of binder content (Char_CC_9%) had globally the best energy performance. It is therefore chosen for the gas emission tests. Char briquettes from peanut shells with 9% of binder content (Char_PNS_9%) offer the second-best performance, hence their choice. The char briquette from cashew nut shells with 10% of binder content (Char_CNS_10%) was also chosen because it has a better energy performance than those with 9% of binder content (Char_CNS_9%).

Table 4 Classification of biomass char briquettes

Stoves	Biomass char briquettes	Pc (kW)	η_{th} (%)	SBT (min/kg$_w$)	SFC (kg$_c$/kg$_w$)	P_f (kW)	Ranks average
"Jambar" Stove	Char_PNS_9%	3	5	3	4	2	3.4
	Char_CNS_9%	5	2	4	2	5	3.6
	Char_CC_9%	1	3	1	3	3	2.2
	Char_PNS_10%	6	6	6	6	4	5.6
	Char_CNS_10%	4	1	5	1	6	3.4
	Char_CC_10%	2	4	2	5	1	2.8
"Malgache" stove	Char_PNS_9%	1	5	1	5	1	2.6
	Char_CNS_9%	6	4	6	3	5	4.8
	Char_CC_9%	2	1	2	1	4	2
	Char_PNS_10%	4	6	3	6	2	4.2
	Char_CNS_10%	5	2	5	2	6	4
	Char_CC_10%	3	3	4	4	3	3.4

3.4 Gas Emissions from Selected Char Briquettes

Results from the Rasi700 Bio flue gas analyzer at one (1) minute sampling intervals were integrated throughout the test to provide the corresponding emission factors.

These integrations were reported per kilogram (kg) of biomass char briquettes, per mega joule (MJ) of biomass char briquette energy, and per total test duration.

The results on gas emissions from the selected biomass char briquettes were obtained only for the "Malgache" stove, due to technical and operational reasons.

3.4.1 CO Emission Factors

The results of the carbon monoxide emission factors are summarized in Table 5. For a better understanding of the analysis of CO emissions, we have listed in Table 6 the emission factors and performance levels achieved by a stove under a low-ventilation scenario as indicated by ISO/TR 19867-3:2018 [15].

Analysis of Table 5 in conjunction with the results in Table 6 shows that, in terms of performance, the "Malgache" stove achieves performance level 1 (see Table 6) for emission rates per time unit, whatever the coal briquette studied. In terms of CO emissions per megajoule of biomass char briquette energy, the "Malgache" stove achieves performance levels 2 and 3 (see Table 6). Clearly, the use of biomass char briquettes in a poorly ventilated "Malgache" stove can be hazardous to human health, since CO emissions are relatively high.

In terms of CO emission factors per kg of charcoal briquettes, Char_PNS_9% has the lowest emission factor value (79.26 g/kg). In the literature, emission factors ranging from 34.2 to 208.35 g/kg for charcoal and biomass char briquettes stoves have been reported [12, 16]. In this study, emission factors are well in this range and corroborate the results found in literature.

Table 5 CO emission factors for selected briquettes.

Samples	CO emission factors		
	g/kg	g/min	g/MJ
Char_PNS_9%	79.26	0.25	2.60
Char_CC_9%	127.35	0.40	4.19
Char_CNS_10%	129.20	0.30	4.25

Table 6 CO emission factors for the low-ventilation scenario [12].

Levels	mg/min	g/MJ
5	≤ 60	≤ 1.4
4	≤ 95	≤ 2.2
3	≤ 160	≤ 3.7
2	≤ 240	≤ 5.5
1	≤ 430	≤ 9.9
0	> 430	> 9

3.4.2 Instantaneous Variation in CO

In this part, we wanted to see the number of times the CO emissions from the different briquettes studied exceeded the limit values set by the WHO (World Health Organization). In other words, the target values of 0.59 g/min for stoves with smoke ducts or ventilated (ACF or ventilated stove limit) and 0.16 g/min for stoves without smoke ducts or not ventilated (SCF or not ventilated stoves limit).

3.4.2.1 Case of Char_PNS_9%

Fig. 6 shows the instantaneous evolution, at intervals of one (1) minute, of CO emissions of Char_PNS_9% during the combustion phase. It clearly showed that during the combustion of Char_PNS_9%, CO emissions did not reach the target value of 0.59 g/min (ACF stove limit). On the other hand, over a wide range of test duration, the target value of 0.16 g/min (SCF stove limit) was exceeded. This value exceeded 84 times out of a total of 122 measurements.

3.4.2.2 Case of Char_CC_9% Briquette

Fig. 7 shows the real-time recording of CO emissions from the combustion of char briquettes from corn cobs (Char_CC_9%). These CO emission trends were also compared with the WHO guideline limit values (0.59 g/min, ACF stove limit, and 0.16 g/min, SCF stove limit).

In contrast to the combustion of Char_PNS_9%, the combustion of Char_CC_9% emitted CO above the limit value of 0.59 g/min.

This value exceeded 40 times out of 130 measurements during the test. The threshold value of 0.16 g/min also exceeded 90 times out of 130 measurements.

3.4.2.3 Case of Char_CNS_10% Briquette

Fig. 8 also shows the real-time recording of CO emissions from the combustion of char briquettes from cashew nut shells. CO emission trends were also compared with WHO guideline limit values (0.59 g/min, ACF stove limit, and 0.16 g/min, SCF stove limit).

As with char briquettes from peanut shells, CO emissions of char briquettes from cashew nut shells remained below the threshold value of 0.59 g/min. However, CO emissions remained above the threshold value of 0.16 g/min in almost the entire test. This value exceeds 124 times out of 130 measurements during the test.

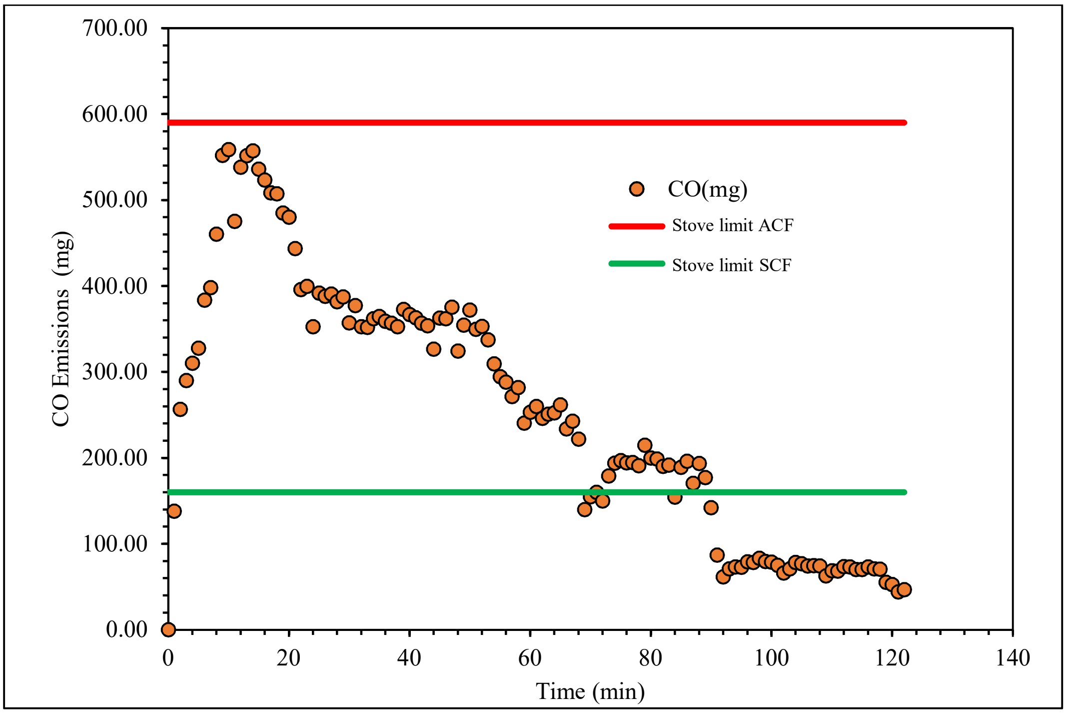

Fig. 6 Evolution of CO emissions during the combustion phase of char briquettes from peanut shells (PNS).

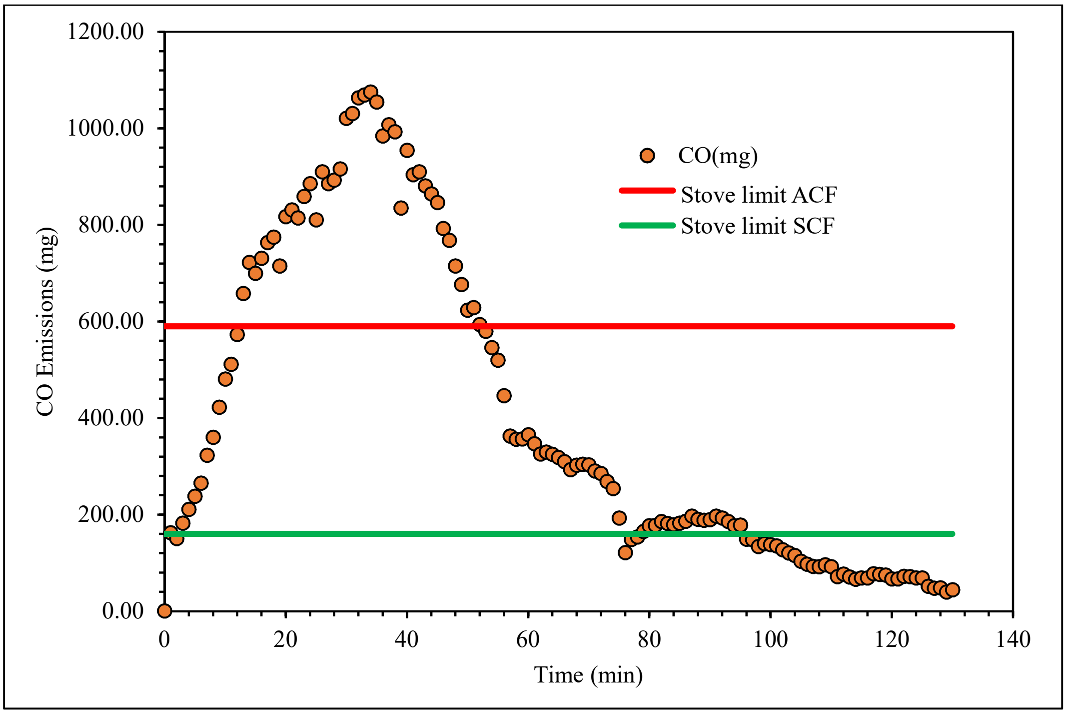

Fig. 7 Evolution of CO emissions during the combustion phase of char briquettes from corn cobs (CC).

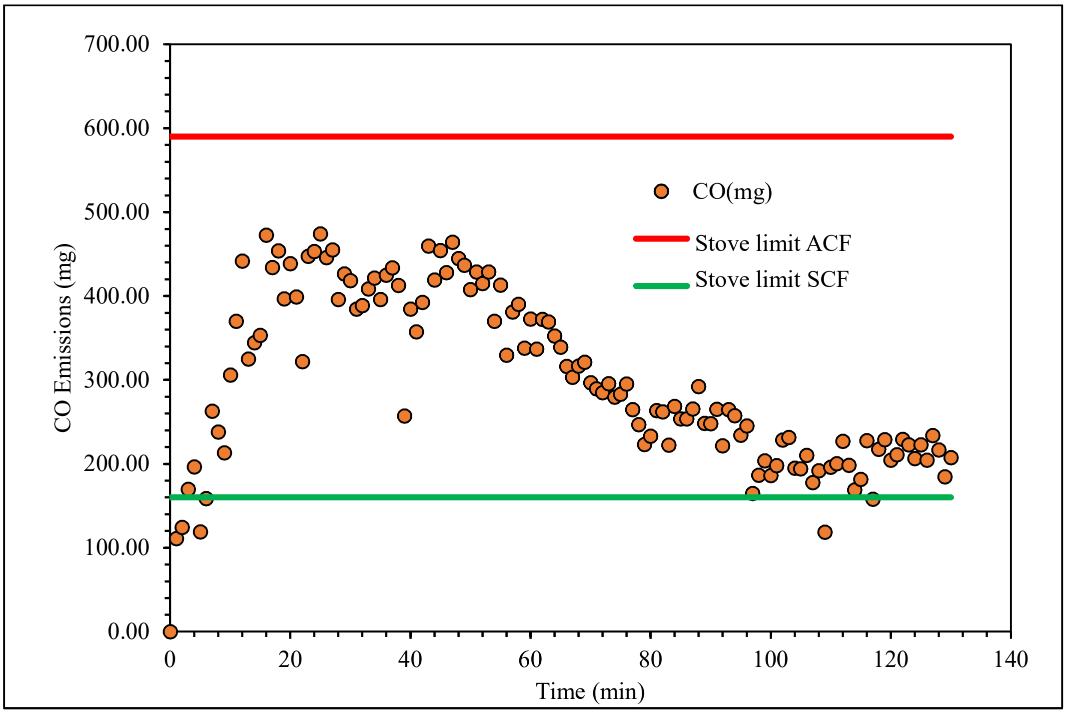

Fig. 8 Evolution of CO emissions during the combustion phase of char briquettes from cashew nut shells (CNS).

Overall, for all the tests carried out, CO emission factors did not exceed the threshold value of 0.59 g/min for any of the three biomass char briquettes studied, whereas the threshold of 0.16 g/min was exceeded by a wide margin (see Fig. 9).

3.4.3 NO_x Emission Factors

Table 7 shows the results of the NO_x emission factor calculations.

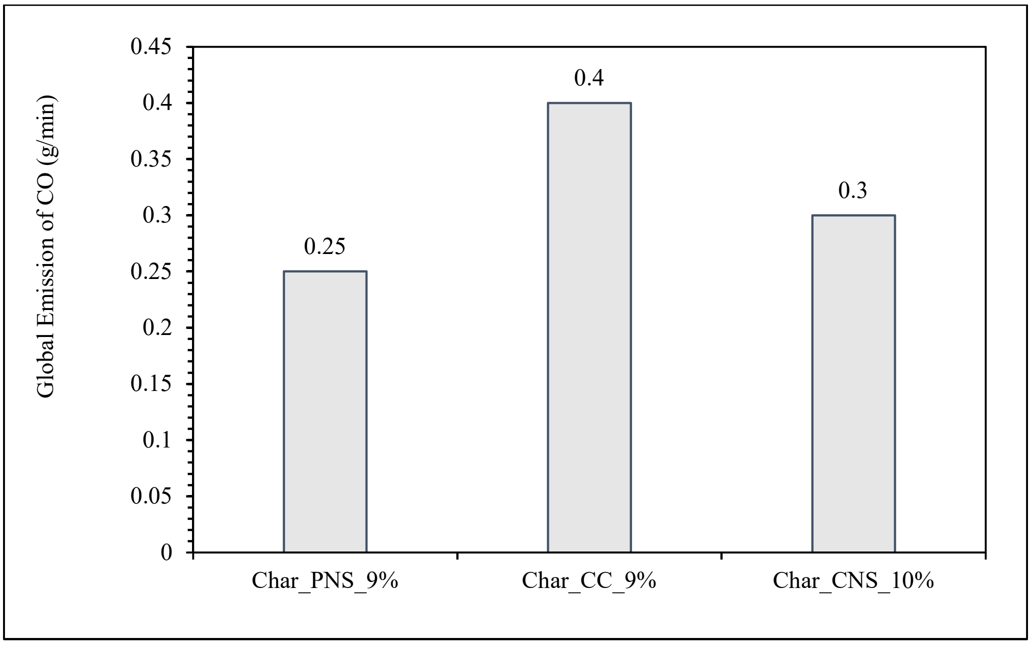

Fig. 9 Total CO emissions during the combustion phase of the different biomass char briquettes.

Table 7 Results of NO_x emission factors.

Samples	NO_x emission factors		
	mg/kg	mg/min	g/MJ
Char_PNS_9%	1.24	3.98	0.04
Char_CC_9%	3.09	9.79	0.10
Char_CNS_10%	2.28	5.32	0.08

Table 7 clearly shows that whatever the basis on which NO_x emission factors are reported, char briquette Char_CC_9% remains the most polluting, and the least polluting is Char_PNS_9%. It should be remembered that NO_x formation is partly due to the nitrogen content of the fuel, but also to the combustion temperature. Elemental analysis clearly showed that the nitrogen content of the Char_CC_9% (1.32%) was higher than that of the others (1.29% for Char_PNS_9% and 1.16% for Char_CNS_10%).

However, NO_x emission factor of Char_CNS_10% is higher than that of Char_PNS_9%. This could be due to a higher temperature during combustion of Char_CNS_10%, because of its higher binder content (or its higher volatile matter content).

The emission factors of these biomass char briquettes, relative to a kilogram of biomass char briquettes, remain much lower than those found by Bhattacharya et al. [16]. Emissions from charcoal-burning stove have been estimated at between 29 and 510 mg/kg. Mitchell et al. [17] also found in their work, a NO_x emission factor greater than 20 mg/kg when using charcoal.

3.4.4 Instantaneous Variation in NO_x Emissions

Fig. 10 shows the instantaneous variations in NO_x emissions per one (1) minute interval for the different biomass char briquettes selected. In Fig. 10 we observe that after briquette ignition, NO_x concentrations rose rapidly within the first 20 min, reaching maximum concentrations of 5.03 mg for Char_PNS_CA_9%, 11.65 mg for Char_CC_9%, and 5.90 mg for Char_CNS_10%.

This rapid rise in NO_x concentration would certainly be due to the increased temperature of the briquette charge at the start of the combustion phase, favoring the reaction between the nitrogen contained in the biomass char briquettes and the oxygen in the air. Over the rest of the test, NO_x concentrations for all biomass char briquettes remained virtually constant, fluctuating between 2.68 and 5.02 mg for Char_PNS_9%, between 8.08 and 11.31 for Char_CC_9%, and between 4.07 and 6.65 mg for Char_CNS_10%.

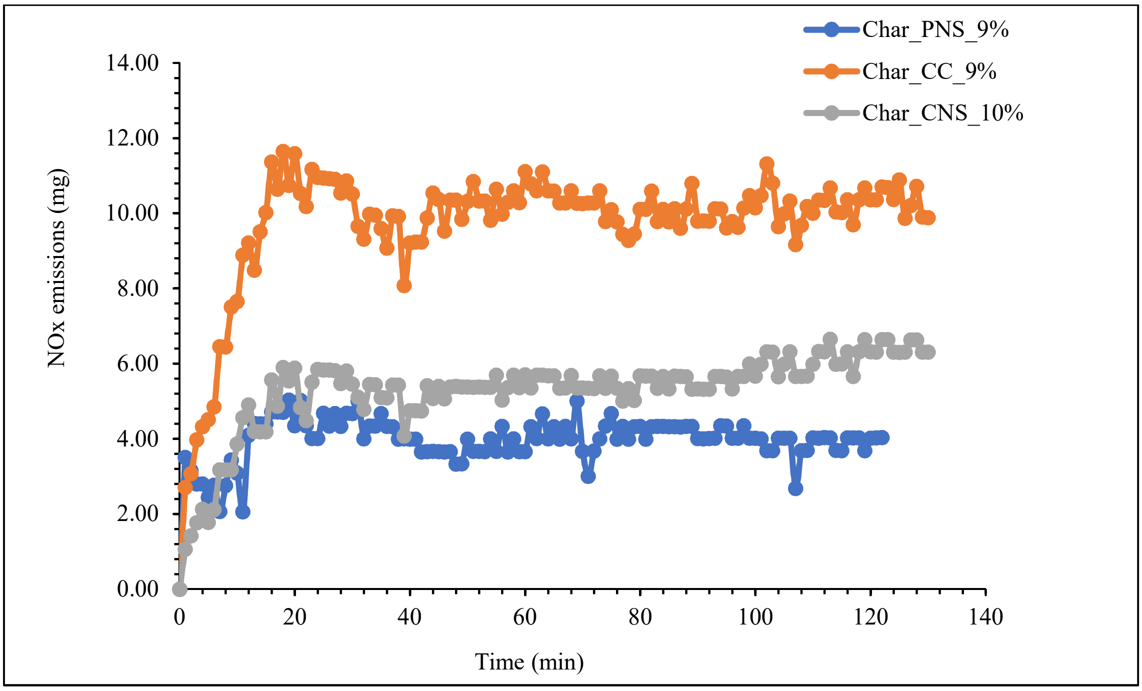

Fig. 10 **Variation in NO_x emissions during the combustion phase of the selected biomass char briquettes.**

These different trends were also observed by Chen et al. [18] who explain that NO_x formation is mainly due to the reaction between fuel nitrogen and oxygen.

4. Conclusion

In this study, we produced 6 different batches of biomass char briquettes. The results obtained from water boiling tests in both a "Malgache" and a "Jambar" stoves were used to determine the energy performance parameters of each biomass char briquette. Based on the energy performance parameters, three (3) biomass char briquettes were selected for the emission tests. The results of energy performance highlighted:

- Biomass char briquettes of corn cob (Char_CC_9%) show the best energy performance, followed by peanut shells char briquettes (Char_PNS_9%) and lastly cashew nut shells char briquettes (Char_CNS_10%).
- Thermal efficiency of "Jambar" stove remained the best compared to the "Malgache" stove. For the "Jambar" stove, thermal efficiency ranged from 11.36% to 23.71%, and for the "Malgache" stove from 10.41% to 15.44%. The average thermal efficiency of the "jambar" stove was 15.68%, while that of the "Malgache" stove was 12.41%.

The combustion of the three (3) selected biomass char briquettes in a "malgache" stove, was performed and CO and NO_x emissions were measured. The concentrations of the various pollutants emitted (CO and NO_x) varied from one biomass char briquette to another. The CO emission factor ranged from 79.26 to 129.20 g/kg while the NO_x emission factor ranged 1.24 to 3.09 mg/kg. These differences are attributed to the characteristics of the biomass char briquettes. It was highlighted that:

- Biomass char briquettes of peanut shells (Char_PNS_9%) had the lowest CO emission factor in milligram per kilogram of fuel;
- Biomass char briquettes of corn cobs (Char_CC_9%) had the highest NO_x emission factor in milligram per kilogram of fuel.

Trends of CO and NO_x emissions gas were discussed and the following results were highlighted:

- Average CO emission factors did not exceed the limit value of 0.59 g/min for all the three biomass char briquettes; however, the threshold of 0.16 g/min was largely exceeded.

- During the combustion of biomass char briquettes, Char_PNS_9%, CO emissions trend did not reach the target value of 0.59 g/min (ACF stove limit). On the other hand, over a wide range of test duration, the target value of 0.16 g/min (SCF stove limit) exceeds 84 times out of a total of 122 measurements.
- Combustion of biomass char briquettes, Char_CC_9%, emitted CO above the limit value of 0.59 g/min. This value exceeds 40 times out of 130 measurements during the test. The threshold value of 0.16 g/min also exceeds 90 times out of 130 measurements.
- CO emissions trend of biomass char briquettes, Char_CNS_10%, remained below the threshold value of 0.59 g/min. However, CO emissions trend remained above the threshold value of 0.16 g/min in almost the entire test. This value exceeds 124 times out of 130 measurements during the test.
- NO_x concentrations rose rapidly within the first 20 min, reaching maximum concentrations of 5.03 mg for Char_PNS_CA_9%, 11.65 mg for Char_CC_9%, and 5.90 mg for Char_CNS_10%. Over the rest of the test, NO_x concentrations for all biomass char briquettes remained virtually constant, fluctuating between 2.68 and 5.02 mg for Char_PNS_9%, between 8.08 and 11.31 for Char_CC_9%, and between 4.07 and 6.65 mg for Char_CNS_10%.

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