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Physicochemical and mechanical properties of biomass coal briquettes produced by artisanal method

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In this study, carbonized peanut shells, cashew shells and millet stalks were used as raw materials to produce coal briquettes. Clay and arabic gum were applied as binders during briquetting by use of manual press. Physicochemical and mechanical tests of the obtained briquettes were conducted. The results show that the lower heating values of coal briquettes remain higher to that of wood; however, their ash contents are very high compared to wood. Combustion of coal briquettes samples show also that coal briquettes of peanut shells, cashew shells, and millet stalks ignite respectively at 312, 202.5 and 150.5°C. Bulk densities of these briquettes are respectively 543, 765 and 579 kg/m^3. Briquette made with arabic gum presents mechanical compressive strength above 1 MPa.

Key words: Coal briquettes, binders, heating value, bulk density, compressive strength.

INTRODUCTION

The use of traditional fuels (firewood and charcoal) in domestic cookers is one of the main causes of domestic air pollution in households in Senegal (de la Sota et al., 2018). Statistical data from the World Health Observatory estimate of 7904 deaths recorded in Senegal in 2016 have been attributed to household air pollution (World Health Organization, 2018). In addition, the use of these fuels causes problems related to the disappearance of the forest cover. According to the national survey of the second project of participatory and sustainable management of traditional and substitute Energies (PROGEDE-2, 2014), more than 6 million cubic meter of wood are consumed as domestic fuel every year in Senegal. In Africa, until 2014, wood energy (firewood and charcoal) accounts for 70% of the energy consumed (Madon, 2017). According to The World Bank and International Energy Agency Report, only 36% of the Senegalese population have access to clean fuels and technologies for cooking (International Energy Agency and The World Bank, 2017). The use of agricultural residues to produce clean cooking energy is one of the possible alternatives to reduce the pressure on natural forests and fight against domestic air pollution, particularly in Senegal. Some biomass densification technologies exist ranging from artisanal processes to industrial processes. Several studies of production of biomass coal briquettes, depending on whether the technology is artisanal or industrial, have been made

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(Bajwa et al., 2018; Godjo, 2017; Lubwama and Yiga, 2018; Meincken and Funk, 2015; Ngusale et al., 2014; Sawadogo et al., 2018). In Senegal, local companies like BRADES, PRONATURA, BIOTERRE, etc. use artisanal process or semi-industrial process to produce coal briquettes for cooking. The lack of control of the artisanal technology (briquetting parameters) presents the risk to bring in the market coal briquettes more polluting than charcoal or firewood. Agriculture and industry in Senegal generate a significant amount of by-products that could be used to produce energy and reduce the amount of wood needed to meet the daily needs of the kitchen. These by-products include peanut shells, cashew nut shells, millet stalks, corn stalks, cotton stalks, rice husks, palm kernel shells, etc. Coal briquettes from agricultural (peanut shells and millet stalks) and industry (cashew shells) wastes were produced, using an artisanal method, in order to evaluate some of their physicochemical and mechanical properties.

The objective of this work is based on the production of biomass coal briquettes in local context in order to suggest ways of improvement.

MATERIALS AND METHODS

Three agricultural wastes like peanut shells (PS), cashew shells (CS) and millet stalks (MS) were used to perform the study. The residues were collected in the region of Ziguinchor (Senegal). Carbonization was performed in a cylindrical metallic drum called “01 fût”. This carbonization is a partial combustion of biomass. Local companies like BRADES in Saint-Louis and ASAPID in Diouloulou (Casamance) use this technique to produce charcoal.

Biomass coal (carbonized material) was crushed using a pestle and mortar. The obtained raw powder was then sieved with a 1 mm sieve to attain a granulometry equal or below 1 mm. Coal briquettes (compressed material) were produced by adding clay and arabic gum as binders. Coal briquettes derived from peanut shells and cashew shells are made with clay and those derived from millet stalks with arabic gum. The clay and arabic gum held respectively a dry mass share of 15 and 20% of the mixture. For the preparation of the gum arabic binder, 1 kg of gum arabic is immersed in 1.5 L of water for one day. After 24 h of immersion, a gelatinous solution of gum arabic is obtained. The clay is mixed directly with the carbonized biomass powder. Afterwards, a quantity of water equivalent to 40% of the total dry mass (mass of clay and carbonized biomass powder) is poured into the mixture until homogenous mixture occurs. Briquetting was done manually by a hammer in a cylindrical mold of 5.3 cm of diameter.

Immediate and elemental analysis of samples of peanut shells, cashew shells and millet stalks, along with derived biomass coal and coal briquettes were performed. Elemental analysis was performed by using an elemental analyzer (VarioMACROcube) following ASTM D5373 and XP CEN/TS 15104 norms. Carbon (C), hydrogen (H) and nitrogen (N) contents were determined, and oxygen (O) content of the sample is obtained by difference. The immediate analysis, conducted in a furnace muffle, was based on the NF EN 1860-2, XP CEN/TS 15148 and XP CEN/TS 14775 norms to determine volatile matter (VM) and ash content (Ash). Fixed carbon content (CF) was derived from the difference (Equation 1).

$$CF(\%) = 100 - VM(\%) - Ash(\%) \quad (1)$$

The analysis for determination of higher heating value (HHV) was performed in a Parr® calorimeter, following the XP CEN/TS 14918 norm. Determination of lower heating value (LHV) on dry basis was based on Equation 2 (Gérard et al., 2016).

$$LHV(kJ/kg) = HHV - (212.2 * H) \quad (2)$$

Peanut shells, cashew shells and millet stalks samples (with particle size of 1 mm) were used to perform thermogravimetric analysis (TGA). The TGA was performed on nitrogen atmosphere (flow rate of 30 ml/min), using 30 to 50 mg of sample and a temperature ranging from room conditions to 1000°C, with a heating rate of 5°C/min.

For coal briquettes, the TGA was performed on a synthetic air atmosphere (flow rate of 100 ml/min) with the same range of temperatures for a heating rate of 10°C/min. Sample mass used is 68.9 mg.

The tests conducted in order to determine the mechanical properties of coal briquettes were also performed by using a testing machine (capacity of 10 kN) to conduct axial compression test until the structure of coal briquette failed. According to Borowski et al. (2017) study, the minimum compressive strength value should be above 1.0 MPa.

Bulk density, true density and porosity of coal briquettes were also determined. The bulk density (ρ_a) is determined by calculating the ratio of mass (m) and volume (V) of the coal briquette (Suttibak and Loengbudnark, 2018).

$$\rho_a = \frac{m}{V} \quad (3)$$

True density (ρ_b) was determined experimentally using a helium pycnometer. Porosity is a measure of the void spaces in a material and is a fraction of the volume of voids over the total volume. Porosity (P) was calculated based on Equation 4 (Karunanithy et al., 2012).

$$P(\%) = \left(1 - \frac{\rho_a}{\rho_b}\right) * 100 \quad (4)$$

RESULTS AND DISCUSSION

Physicochemical composition

The physicochemical analyses carried out under this article concern the immediate analysis, the elemental analysis and the determination of the calorific value. Table 1 shows the results of immediate and elemental analysis a as well as calorific value determination.

When comparing the percentages of fixed carbon and volatile matter among both biomass coals and biomasses, larger percentages of fixed carbon and smaller percentages of volatile matter were observed in biomass coals. However, the percentages of ash are lower in biomasses. The higher percentages of ash in biomass coals could be explained by the partial combustion observed during carbonization beginning. For coal briquettes, we remark also, that by adding clay in biomass coals of peanut shells and cashew shells the calorific values and contents of fixed carbon decrease

Table 1. Immediate and elemental analysis, and calorific value in dry basis.

Samples	Immediate analysis on dry basis (% mf)				Elementary analysis on dry basis (% mf)				calorific value on dry basis (MJ/kg)
	E	VM	CF	Ash	C	H	N	O	LHV
Biomass									
PS	9.04	72.89	24.34	2.77	52.02	5.74	0.95	41.29	19.33
CS	7.80	80.80	16.70	2.50	59.06	6.99	0.43	33.52	21.58
MS	7.66	74.44	21.56	1.00	45.92	5.43	0.52	48.13	16.52
Biomass coal									
PS	6.99	10.66	64.96	24.38	64.71	1.61	2.34	31.34	23.37
CS	10.60	8.93	78.02	13.05	78.27	1.24	1.14	19.35	27.31
MS	14.36	9.85	54.41	35.74	56.70	0.56	0.88	41.86	19.49
Coal briquette									
PS	4.31	8.19	56.13	35.68	56.56	1.55	0.94	40.95	19.49
CS	5.43	19.13	62.89	17.98	71.76	2.72	0.95	24.57	26.52
MS	8.00	21.97	58.74	19.29	62.84	2.31	0.76	33.99	22.22

PS: Peanut shell; CS: Cashew Shell; MS: Millet stalk; E: Moisture content; VM: Volatile matter; CF: Fixed carbon; C: Carbon; H: Hydrogen; N: Nitrogen; O: oxygen; LHV: Lower Heating Value.

and ash contents increase. Contrary effect was observed with coal briquette of millet stalks made using arabic gum as binder.

Calorific value remains the most relevant combustion property for determining the suitability of coal briquette as fuel. Calorific value gives an indication on the quantity required to generate a specific amount of energy. Lower heating values of coal briquettes were found to be higher than that of wood; however, their ash contents are very high compared to wood (McKendry, 2002). It would be necessary to reduce this ash content because it affects the combustion of the briquette.

Thermogravimetric analysis

The thermogravimetric analysis (mass loss and mass loss rate) experiments are shown in Figures 1a, 1b, 2a and 2b. In Figures 1a and 1b, we show the variation of mass loss and mass loss rate with temperature during decomposition of biomass samples into nitrogen atmosphere.

As observed on TGA curves of Figure 1a, thermal decomposition of the three biomasses studied is done in three steps. The first part occurs mainly below 200°C, and as shown in Figure 1b, the mass loss is accompanied by peaks, distinct at about 100°C, representing the mass loss rates of biomass samples (0.08%/min for peanut shell and millet stalks and 0.23%/min for cashew shell). This thermal behavior of biomass is mainly related to the evaporation of free water in the biomass and also to the initial pyrolysis of hemicelluloses and lignin. This first slight mass loss was ascribed to the evaporation of surface moisture at 30-100°C, crystal water at 100-150°C and light volatile components (Saikia et al., 2015). The second part is between 200 and 410°C, where the maximum rates of mass loss appear (Figure 1b). According to Shinde and Singarvelu (2014) study, devolatization (2nd phase) occurred at temperatures between 200 to 500°C. Ábrego et al. (2018) and Liu et al. (2018) found maximum decomposition rates in the same range of temperature (200 to 500°C). The strong devolatilization of hemicelluloses, cellulose and lignin is obtained in this area. The largest mass loss of three biomasses has occurred in this area. The mass loss rates obtained are 3.00%/min, 2.67%/min and 3.88%/min respectively for peanut shell, cashew shell and millet stalks. For temperatures above 410°C, the decomposition of the biomass continues. This decomposition is associated with pyrolysis of lignin at high temperature. Slow pyrolysis is almost complete after about 600°C. Lignin, as the most complex and stable component, slowly decomposed and mainly converted into char (Jones et al., 2015). Above 600°C, mass loss rates are very close to zero, indicating that mass losses can be neglected. The thermal decomposition of the three coal briquettes into synthetic air atmosphere are shown in Figure 2a and b.

It is observed in Figures 2a, small mass losses for the three coal briquettes (losses more accentuated with coal briquette of millet stalks) during the combustion initial phase (water release). We have also remarked that coal briquettes ignition temperatures of peanut shells, cashew shells, and millet stalks are respectively 312, 202.5 and

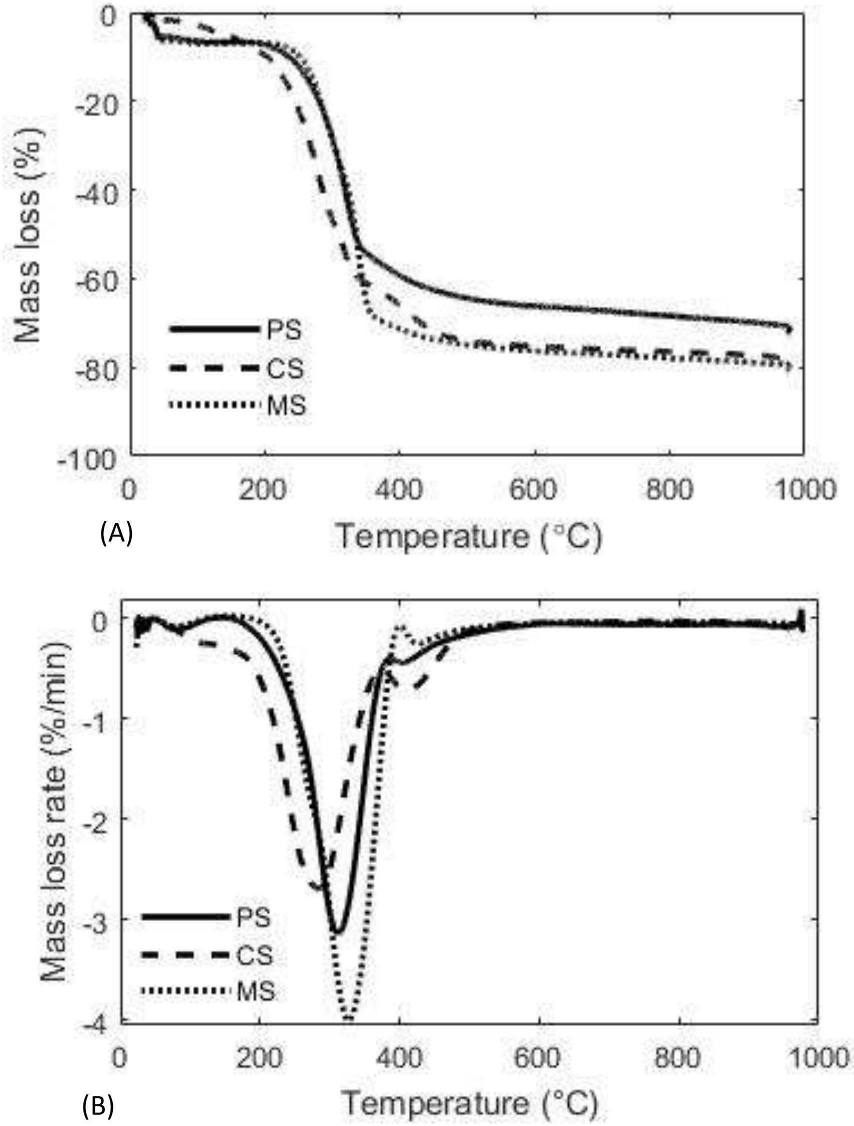

Figure 1. (**a**) Mass loss from thermal decomposition (TGA) of biomass samples (**b)** Mass loss rate from thermal decomposition (TGA) of biomass samples.

150.5°C. Ignition temperatures of coal briquettes from peanut shells and millet stalks are considered lower than those found by (Protásio et al., 2017) for fresh babassu nut shell and by Sahu et al. (2010) for charcoal. Massaro et al. (2014) found ignition temperatures for fines briquetted coal with municipal solid waste plastic binders ranging from 249 to 309°C. After the drying phase, the combustion of coal briquettes leads to higher mass losses (63, 80 and 82%, respectively for peanut shells, millet stalks and cashew shells). However, for coal briquettes of millet stalks and cashew shells, we observe decomposition phases which occurred respectively at temperatures of 150.5 to 353°C and 202.5 to 403.5°C (Figure 2a). These phases could be attributed to the degradation of volatile matter. This phase of decomposition is not observed for coal briquette of peanut shells (the volatile matter content is low). The large mass losses observed after initial combustion phase can be explained by maximum peaks of mass losses rates obtained (Figure 2b). We observe a doubling of the peaks corresponding to the degradation of volatile matters of coal briquettes of millet stalks and cashew shells.

Physical and mechanical properties of coal briquettes

Mechanical strength tests of coal briquettes were carried out in order to evaluate the compressive strengths. It has

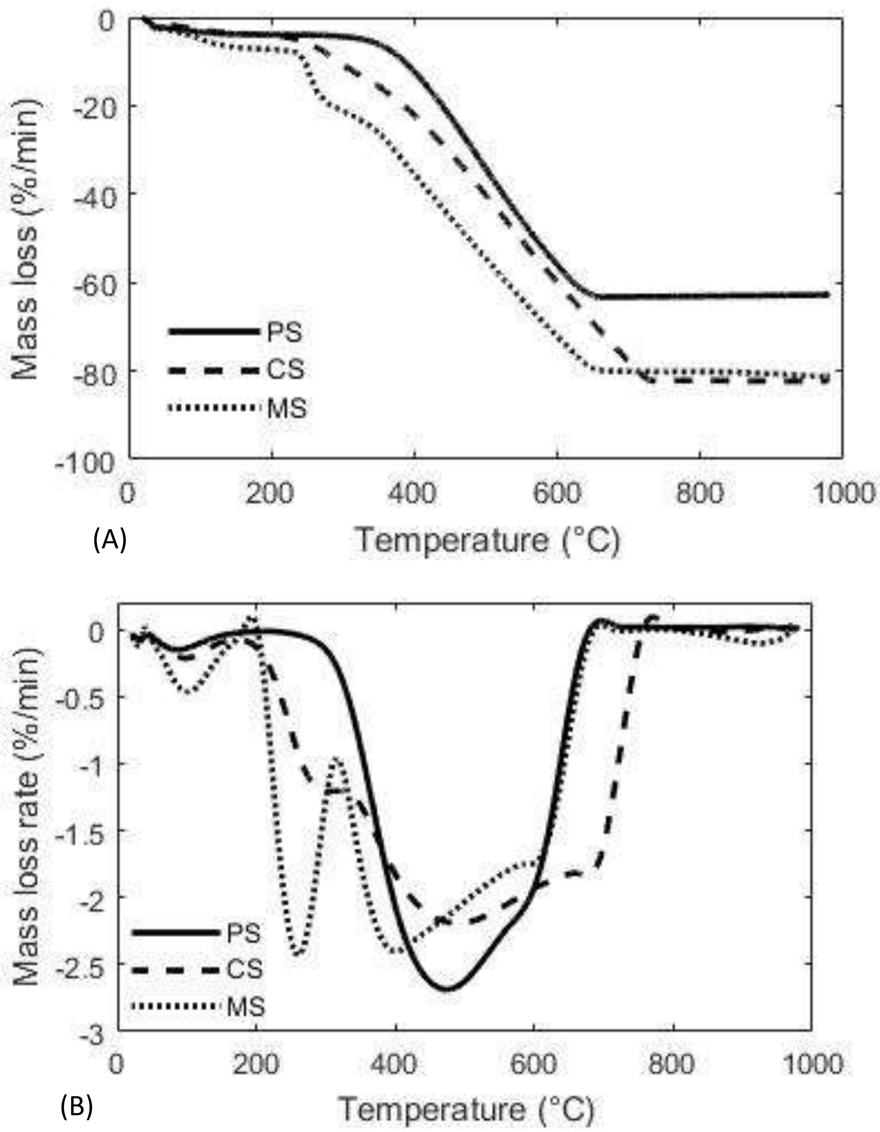

Figure 2. (a) Mass loss from thermogravimetric analysis of coal briquettes **(b)** Mass loss rate from thermogravimetric analysis of coal briquettes.

been noted that during transport and storage operations, significant amounts of materials can be lost due to their fragility and crumbling. Hence, the interest of carrying out these tests in order to guarantee the briquette a minimum resistance (compressive strength) allows it to be held mechanically in the face of certain stresses (for example falls or contacts during storage). It is also noteworthy that physical properties like bulk density or porosity can significantly affect process rates during combustion. According to Ryu et al. (2006) study, the ignition speed rate is inversely proportional to the bulk density, while the burning rate tends to decrease linearly. We present in Table 2 the physical and mechanical properties of the coal briquettes.

Table 2 shows that coal briquette of peanut shell has the lower bulk density, the higher porosity and the lower compressive strength. The compressive strengths of coal briquettes of peanut shells and cashew shells are below 1 MPa. According to the study of Borowski et al. (2017), these briquettes are not suitable for transport and storage.

Porosity plays a crucial role in the exchange of water (water uptake) during the absorption or desorption cycles depending on the storage medium (effect of relative humidity). This implies that during storage in places where relative humidity is not controlled, briquettes will undergo cycles of absorption and desorption to maintain equilibrium.

Coal briquettes had high porosity as those of briquettes palm kernel shell and those of some charcoal from

Table 2. Physical and mechanical properties of coal briquettes.

Coal briquette	Bulk density (kg/m^3)	True density (kg/m^3)	Porosity (%)	Compressive strength (MPa)
PS	543.00	1817.00	70.12	0.34
CS	765.00	1616.00	52.70	0.88
MS	579.00	1700.00	65.93	1.66

different plant species (Bazargan et al., 2014; Keech et al., 2005). Bulk density is known to influence the burning rate and the specific fuel consumption of the briquettes (Križan, 2009).The average bulk density of coal briquettes of peanut shells and millet stalks, and, cashew shells were found to be close respectively to those of rice hull coal briquette (500 kg/m^3) and corn cob coal briquette (730 kg/m^3) (Tuates et al., 2016).

Conclusion

Carbonization with partial combustion of the agricultural waste leads to the formation of high ashes contents. Nevertheless, this technology gives coal with satisfying fixed carbon (above to 50 %). Clay, as a binder, negatively affects the quality of the coal briquette by decreasing its calorific value and increasing its ash content. Ashes contents of coal briquette of peanut shells, cashew shells and millet stalks are respectively equal to 35.68, 17.98 and 19.29%. In this study, we found also that the lower calorific values of coal briquettes of peanut shells, cashew shells and, millet stalks are respectively 19.49, 26.52 and 22.22 MJ/kg. The results show also compressive strength of coal briquettes of peanut shells, cashew shells and millet stalks are low (0.34, 0.88 and 1.66 MPa, respectively).

Based on the results obtained, the following conclusions can be drawn to produce quality char briquettes:

i) The partial combustion carbonization of the biomass has to be improved or avoided;
ii) Optimal binder ratio has to be defined to produce cohesive coal briquette with low ash content;
iii) Optimal molding pressure to be defined (mechanical properties).

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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