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Characterization of Biofuels from the Carbonization of Incinerable Solid Waste for the Region of Dakar (Senegal)

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Abstract: A characterization campaign (collection and sorting) first made it possible to know the composition and the flow of household and similar waste in Dakar area and to see the methods of energy recovery possible in this case the production of biofuels. The carbonization method is used to observe the optimum conditions for preparing solid waste briquettes by a molding process with a hand press. Subsequently, we determined the carbonization efficiency and some physical parameters that characterize the quality of biofuels produced (dry matter, moisture, ash content, calorific value, density). The effect of the binder level used in the formulation of the briquettes was also studied.

Key words: Waste, collection, sorting, carbonization, biochar, calorific value, density, humidity

INTRODUCTION

Energy demand is growing as fossil reserves decline exponentially around the world. Among alternative energy resources, biomass is an important renewable energy resource because of its attractive properties such as low production costs, low greenhouse gas emissions and low acid gas emissions. The household waste and assimilated, when burned, pollute the environment, otherwise cause drainage obstruction during the rainy season or facilitate the spread of bacteria when piled up. Therefore, the search for biomass energy from solid waste has attracted considerable interest. Turning this abandoned waste into renewable energy resources such as fuel briquettes is the focus of this study. Recently, several studies have been carried out for the formulation of biomass briquettes for example the study on the possibility of producing durable, binderless briquettes from sawdust and wheat straw (Smith *et al*., 1981) from olive waste and stationery waste (Rosenvold *et al*., 1982) and wood residues (Janikowski and Stenberg, 1989). Chin and Siddiqui also used a piston molding process to densify sawdust, rice husks, peanut hull, coconut fiber and palm fruit fiber, respectively (Chin and Siddiqui, 2000). Li *et al*. (2001) studied the high-pressure compaction of municipal solid waste to form a densified fuel. Other studies have focused on extruded waste briquettes. Kaliyan and Morey (2009) reviewed and discussed factors affecting the strength and durability of densified biomass products (Taguchi, 1990).

The feasibility of formulating biomass briquettes from solid waste as studied in the literature, generally concerns biomass briquettes made directly from bio-waste. Also, the optimal conditions for preparing the fuel briquette from solid waste using the carbonization method have rarely been studied. Furthermore, a study of the effect of percent binder on certain parameters (ash content, Calorific value, dry matter, humidity and density) of the waste briquette was rarely undertaken. In this research, after a collection and sorting campaign carried out in Dakar area (Senegal), we made briquettes based on incinerable solid waste (cardboard, wood, paper, unclassified fuels, Textiles and Sanitary Textiles (TTS) by the charring method. These briquettes are characterized by studying the effects of the binder rate, the carbonization efficiency, the calorific value evolution, the density, the ash rate, the humidity and the dry matter. This is part of the energy recovery of solid waste and the search for alternative solutions of charcoal and firewood by biofuel.

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MATERIALS AND METHODS

The first step of this research is to collect waste in the study area (Dakar Region, Senegal) with 70 waste bags distributed in households of 15-25 people. Households collected waste for one day and bags were recovered the next day at the same time. In order to define the weight of the sampling to be sorted, the waste was collected at the household level under the same conditions. The characterization and quantification of the fluxes was then carried out using the household waste characterization method (MODECOM) protocol and associated standards (Environment and Energy Agency (France), 1993; Anonymous, 1996a, b).

Most often, solid waste contains a small amount of water. It is important to dry them before processing as this water has a negative impact on the carbonization efficiency. This drying step which lasts between 3 and 6 days in the Sun, allows not exceeding more than 20% of humidity what is adequate for carbonization stage. Carbonization is the thermochemical decomposition of organic matter under controlled conditions. This step is the most important part of the process. It makes it possible to pass the incinerable solid waste (unclassified fuels, wood, textiles and sanitary textiles, cardboard, paper) from the state of biomass to the state of carbon powder. This carbon powder is obtained by carbonizing dry waste in a controlled atmosphere (limited oxygen supply). This process makes it possible by raising the temperature to extract waste the liquefiable and gasifiable fractions (humidity and plant/volatile organic matter) in order to keep only the carbon and some minerals (future ashes). At the same time, all elements that could be a source of smoke, odors and sparks are eliminated. The carbonization is done in a metal furnace consisting of a cylinder placed on three feet to lift a few centimeters, a lid and a chimney. The efficiency is improved if the waste to be carbonized is stacked or arranged before being introduced into the carbonizer which is filled to the brim to reach a load of 2-3 kg (Fig. 1). The carbonization lasts between 30 and 60 mins. The course of carbonization is controlled in two ways (Fig. 2).

Smoke color control: The smoke is black and yellow at the beginning because of the water vapor and some volatiles contained in the waste that is extracted. This smoke turns into a thick white smoke then to a blue color. This blue color indicates that carbonization is in progress.

Control by the vents: This second control is to probe the mass to carbonize with a stick introduced through the vents. The absence of resistance means that the carbonization is complete.

Table 1: Plasticity properties of clay (atterberg limits)

Variables	Values
Liquidity Limit (LL)	36.1
Plasticity Limit (LP)	17.7
Plasticity Index (IP)	18.4

Fig. 1: Filling the carbonizer and pre-closing before firing

Fig. 2: Control of carbonization and movement of vents

After carbonization, the milling is done by pouring the contents of the carbonizer into a bin. Carbonized waste cannot be used directly as fuels because it is too friable. In order to prepare their shaping coal briquette, it is necessary to crush them coarsely and mix them with a binder and water.

The binder (here clay) allows the agglomeration into a solid mass of the carbonized waste powder. The clay is ground with a mortar/pestle and screened before being used as a binder. In this study, the clay used is not very plastic and has the properties summarized in Table 1.

We have varied the binder content in mass between 10 and 20% of the mass of carbonized waste. A percentage of unsalted water (distilled water) is added relative to the mass of carbonized waste. The percentage of water depends on the type of waste (25% for textiles, 75% for unclassified fuels and 100% for other types of waste) (Fig. 3).

The final step in the biofuels formulation process is bricklaying. The method used follows the principle of a manual press made in the laboratory with a mold to produce cylindrical briquettes (Fig. 4). The material enters the press in the form of paste and comes out in the form of coal briquettes. The last step is to dry the biofuel (Fig. 5). The drying lasts between 3 and 7 days.

After the production phase, the coals are characterized by determining several parameters. These measurements were carried out following protocols for

Fig. 3: Carbonized waste powder

Fig. 4: Biofuel formulation process

Fig. 5: Drying biofuels (wood, cardboard, paper, unclassified fuels, textiles and sanitary textiles)

measuring the physicochemical characteristics of solid domestic fuels. Charcoal physicochemical characteristics are used as reference values

Dry matter and humidity: The dry matter represents the dry fraction of the biochar. Humidity on crude represents the amount of water present in the coal relative to its wet mass.

For the determination of dry matter and humidity, a known mass sample is placed in a calibrated porcelain crucible and dried in an oven at 105°C for 24 h until constant mass. During this drying, volatile compound such as Volatile Fatty Acids (VFAs) are volatilized. The difference in mass, therefore, corresponds to the total Dry Matter (DM) or Organic Matter (OM) contained in the sample as given in Eq. 1:

$$MS\left(\frac{g}{1}\right) = \frac{\text{Mass at } 105°C}{\text{Fresh mess}} \times 1000 \quad (1)$$

Ash rate: The ash content represents the ash mass remaining after a complete incineration of the fuel with respect to its dry mass. It was determined with a Nabertherm LV5/11 muffle furnace. The sample is incinerated at 550°C and the resulting residue weighed. The weight of the residue is calculated by deducting the tare. The result is expressed in % of the sample as given in Eq. 2:

$$\% = \frac{(w\text{-}t)5100}{p.e} \quad (2)$$

Where:

w = The weight in grams of the crucible and ashes after calcination
t = The tare of the crucible (g)
p.e = The test portion (g)

Calorific value: The apparatus used is a calorimetric bomb (Oxygen bomb calorimeter) adapted for the determination of the calorific value of biofuels.

Apparent volumetric mass: Bulk density is the actual fuel mass present in a given volume. It gives an account of the shape, porosity and grain size of the fuel (GRET *et al*., 2016). A pyknometer was used for its determination.

RESULTS AND DISCUSSION

Characterization campaign: The characterization campaign (collection, sorting and experimentation) made it possible to determine the production flow (539045.81 t/year) and the composition of household waste and assimilated from Dakar area with an average production of 171.82 kg/inhabitant/year. Incinerable waste (wood, cardboard, paper, unclassified fuels and sanitary textile textiles) accounted for 177483.45 ton/year (33.88 % of total flows) and recyclable waste (plastics, metals) 40511.73 ton/year (7.73% of total flows). Storable waste (incombustible unclassified) represents 61032.47 ton/year (or 11.65% of total flows) and the potential for organic recovery (putrescible, fine elements,) represents a flow of 244814.64 ton/year (46.73% of the total waste produced) (Fig. 6). Compared to the national average (16% for incinerable waste, 67% for organic waste), these results show a high potential for energy recovery (carbonization) in view of the massive quantities of incinerable waste produced annually as well as the fermentable fraction which also gives a strong potential for organic recovery (biogas). The rest of the work presents the formulation and characterization of biofuels by carbonization.

Carbonization efficiency: Table 2 shows the post-carbonization efficiency of the incinerable solid

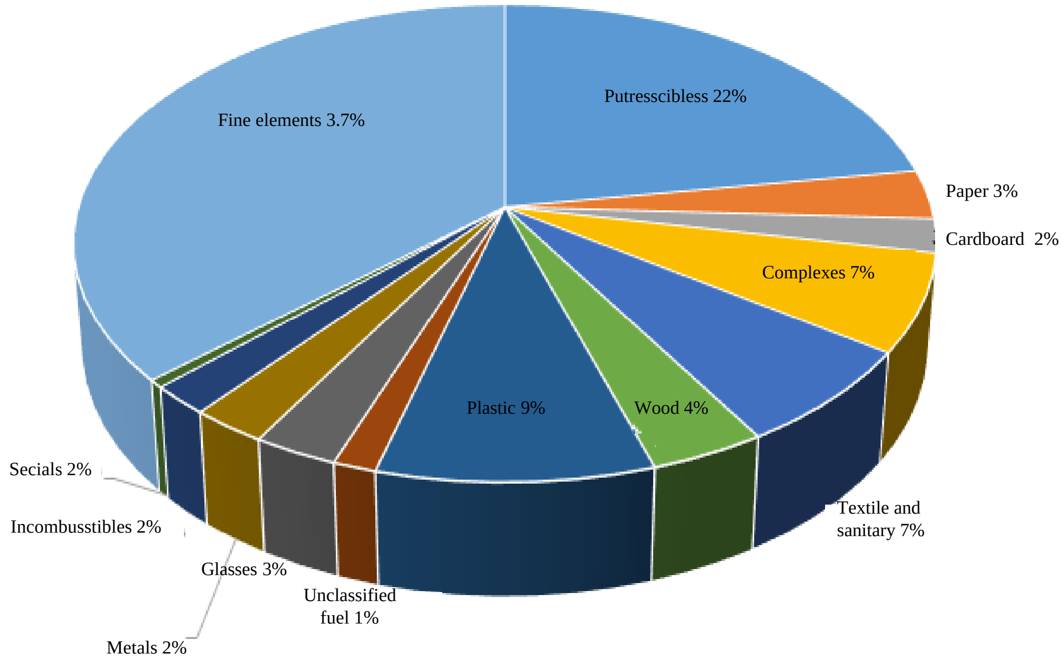

Fig. 6: Average composition (%) of household and similar waste in Dakar area

Table 2: Carbonization efficiency of incinerable waste

Matter/mass	Textiles and sanitary textiles	Paper	Wood	Cardboard	Unclassified fuels
m_i (g)	9.15	9.3	8.57	7.75	8.2
m_c (g)	6.3	6.2	6.3	6.5	6.2
m_f (g)	7.7	8.7	7.55	7.1	7
η (%)	50.9	19.35	44.9	52	60
η = 45.43%					

waste. Efficiency ranges from 19.35-60% with an average of 45.43%. The study has the lowest yield because of its lightness compared to other types of waste. Uncategorized carbonized fuels have an average of 60% due to their composition. These values reflect the amount of carbonized material obtained after incomplete combustion of a given material. We show that one ton of raw waste produces 454.3 kg of carbonized waste.

Characterization of waste coals: The following measurements were taken after a drying time of one week and storage for more than two weeks in a completely cleared area. The same process of making coal was used for all biofuels.

Dry matter: Table 3 shows the dry matter results of biofuels and charcoal (reference). Coals of textiles and sanitary textiles, paper, cardboard, wood and charcoal (reference) have high dry matter content (>94.09 %) in contrast to unclassified fuel coals that have a low one (88.4%). Biofuels from unclassified fuels and coals from textiles and sanitary textiles by their composition absorb less water than other biofuels because they were more saturated with an absorption rate of 75 and 25%, respectively, unlike other types of biofuels (100-150%).

Table 3: Dry matter of biofuels and charcoal (reference)

Types of waste	MS (%)	MS (g/L)
Textiles and sanitary textiles	94.09	940.9
Unclassified fuels	88.4	884
Paper	97.13	971.3
Cardboard	97.27	972.7
Wood	97.98	979.8
Charcoal (Reference)	94.4	944

Table 4: Biofuels and charcoal humidity (reference)

Types of waste	Humidity (%)
Textiles and sanitary textiles	5.9
Unclassified fuels	11.6
Paper	2.87
Cardboard	2.73
Wood	2.02
Charcoal (Reference)	5.6

Humidity: Table 4 gives the humidity of biofuels and charcoal (reference). Paper, wood, and cardboard coals have low humidity compared to control charcoal (5.6%), unlike coals of textiles and sanitary textiles and unclassified fuels with higher humidity. In fact, carbonization which is the last step to obtain the finished product, made it possible to evacuate the water present in the biomass for charcoal, paper and charcoal.

Table 5: Biofuels and charcoal ash rate (reference)

Types of waste	Ash rate (%)
Textiles and sanitary textiles	43.52
Unclassified fuels	50.62
Paper	73.26
Cardboard	72.13
Wood	29.46
Charcoal (Reference)	4.26

The different processes during formulation have an impact on the ability of coals to store water. Coals that were composed of water before the final drying can easily regain it because it already had "Its place" in the product as for unclassified fuels contrary to other coals that have retracted and have not taken over. Coals of unclassified fuels are sensitive to humidity, so, they must be dried long enough outdoors and stored in a very dry place.

Ash rate: In Table 5, the results for waste biofuels and charcoal (reference) are presented. The results which follow present the evolution of the ash rate of the biofuels according to the rate of binder.

Textiles and sanitary textiles: Figure 7 shows the evolution of the ash content as a function of the binder content which varies from 10-20% with a margin of 1%. The average ash content for TTS briquettes is 43.52%. This value means that for one ton of briquette burned gives 435.2 kg of ash.

We note that the ash rate evolves in a sawtooth depending on the binder rate. For briquettes with binder content >15%, the ash content is higher than the average (43%) contrary to briquettes with a binder content of <15% where their ash content is between 41 and 42% except the briquette with a binder content of 11% which has an ash content higher than 45%. For the latter, this rate may be due to inhomogeneous mixing between the binder, the carbonized product and water.

Paper: We present in Fig. 8, the evolution of the ash content of paper briquettes as a function of the binder content which varies from 10-20% with a margin of 2%. The average rate is 73.26%. The ash content is progressively increasing overall depending on the rate of binder. The lower the binder rate, the higher the ash rate. This is due to the composition of the material which contained a lot of ash after carbonization.

Wood: Figure 9 represents the evolution of the ash content as a function of the binder content which varies from 10-20% with a margin of 1%. The average rate for wood briquettes is 29.46%. We note that the rate of ash evolves decreasing in general according to the rate of binder. For briquettes with binder content greater than 15%, the ash content is >30%, unlike briquettes with an ash content of <15% where their content is between 25 and 27%.

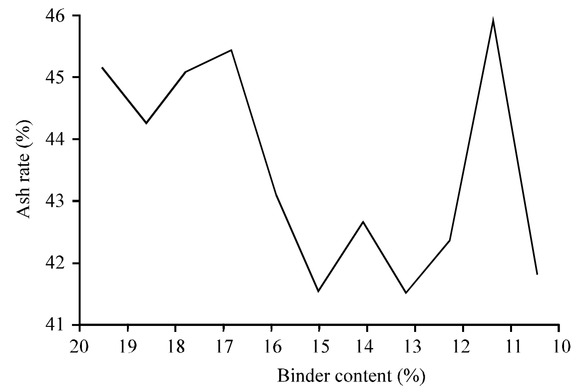

Fig. 7: Evolution of the ash content of biofuels of textiles and sanitary textiles according to the binder rate

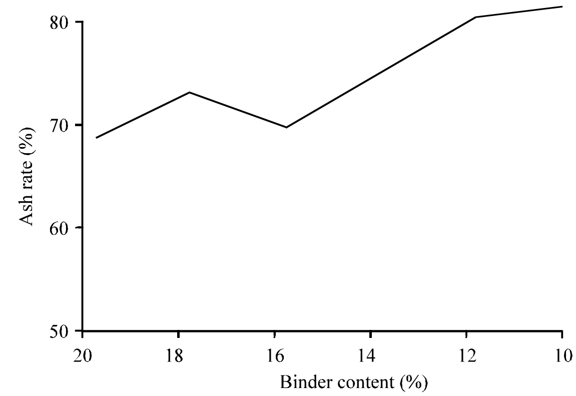

Fig. 8: Evolution of the ash content of paper biofuels according to the binder rate

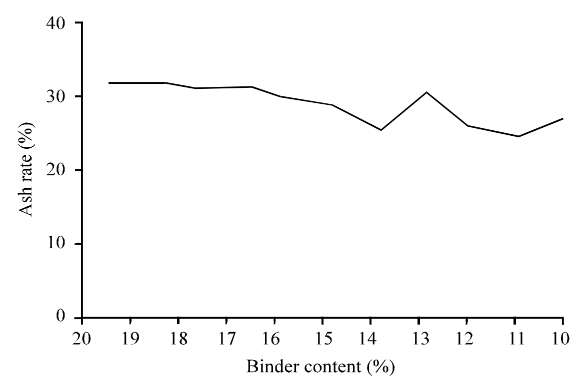

Fig. 9: Evolution of the ash content of biofuels according to the binder rate

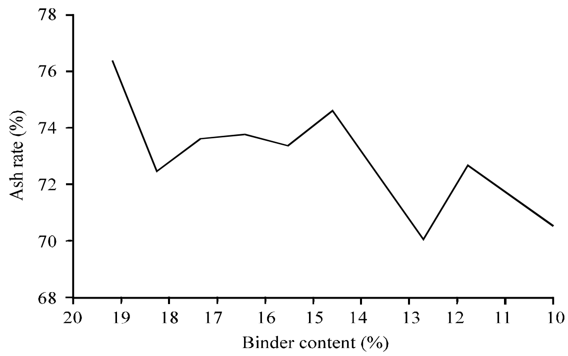

Fig. 10: Evolution of the ash content of cardboard biofuels according to the binder rate

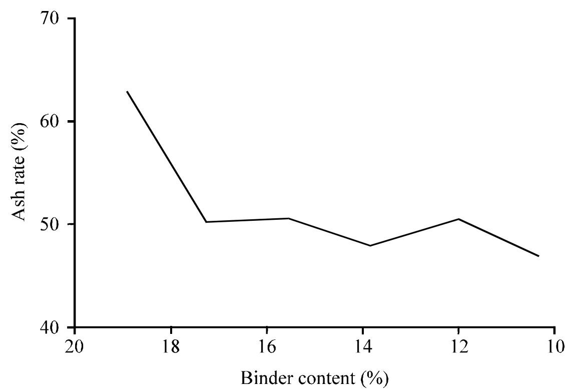

Fig. 11: Evolution of the ash content of non-classified fuel biofuels according to the binder rate

Cardboard: Figure 10 shows the evolution of the ash content as a function of the binder content which varies from 10-20% with a margin of 1%. The average rate for wood briquettes is 72.13%. The ash rate evolves in a sawtooth depending on the binder rate. For briquettes with binder content >14%, the ash content is >71%, unlike briquettes with an ash content of <14% where their ash content is between 68 and 69%.

Unclassified fuel: Figure 11 represents the evolution of the ash content as a function of the binder content which varies from 10-20% with a margin of 2%. The average rate for unclassified fuel briquettes is 50.62%. The ash rate changes decreasingly depending on the level of binder, the higher the binder rate, the lower the rate of ash.

Charcoal (reference) has a very low average ash content of <5%. This is related to its low mineral content (GRET *et al*., 2016). The heterogeneity of the quality of the fuel due to a variable composition (branches, bark, trunks and different species) and variations in the production methods are noticeable. Coals made of household waste and similar have high ash levels (29-70%). These rates are mainly related to the significant presence of silicon oxide in waste and sand. They are also linked to the use of clay, a mineral compound in significant amount as a binder. Dust deposits can increase the rate of ash depending on the season during the final drying out. The evolution and the differences in the rate for the same types of briquettes show a certain heterogeneity of the product which is directly related to the precision of the mixture (water, carbonized waste, clay) and to the variable quality of the carbonization.

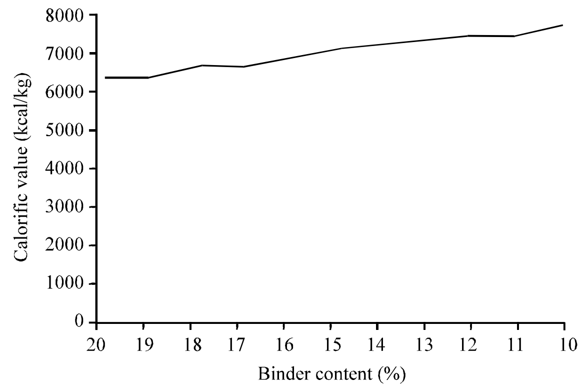

Fig. 12: Evolution of the calorific value of TTS biofuels as a function of the binder content

Calorific value: We used the calorific value of charcoal as a reference (28,000 kJ/kg or 6698.6 kcal/kg). The section below shows the evolution of the biofuels calorific value as a function of the binder content.

Textiles and sanitary textiles: In Fig. 12, we represent the calorific value of the TTS biofuels evolution as a function of the binder content which varies from 10-20%. The values of TTS biofuels calorific values are high compared to the calorific value of charcoal (reference). The average value is 6600 kcal/kg. We notice that the calorific value evolves more and more according to the rate of binder. Starting from 15% of binder, we obtain a calorific value higher than that of the control charcoal.

Paper: Figure 13 represents the calorific value of the paper biofuels evolution as a function of the level of binder which varies from 10-20% with a pitch of 2%. Calorific value values are lower than that of control charcoal (6690 kcal/kg). The average value of paper biofuels is 5900 kcal/kg.

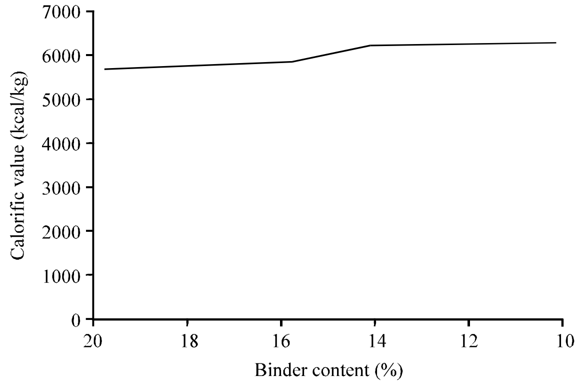

Fig.13: Evolution of the calorific value of paper biofuels according to the rate of binder

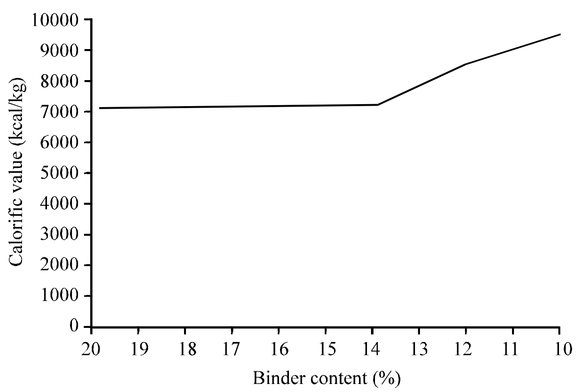

Fig.14: Evolution of the calorific value of biofuels of unclassified fuels according to the rate of binder

Unclassified fuels: The calorific value of the unclassified fuels evolution as a function of the binder content which varies from 10-20% is represented in Fig. 14. Calorific values of unclassified fuels biofuels are very high compared to that of charcoal (reference). With binder content of 10%, we obtain a heating value 1.4 times higher than that of the control charcoal. The average value is 6780 kcal/kg.

Wood: Figure 15 shows the evolution of the calorific value of biofuels based on the binder content which varies from 10-20%. The calorific values of biofuels are similar to the calorific value of charcoal (reference). They are slightly higher from mixtures with binder levels below 17%. The average value is 7000 kcal/kg.

Cardboard: In Fig. 16, we represent the calorific value of the cardboard biofuels evolution as a function of the binder content which varies from 10-20%. The values of the calorific values of cardboard biochar are lower than

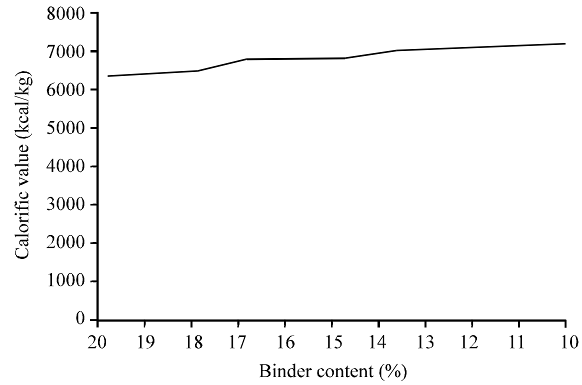

Fig. 15: Evolution of the calorific value of biofuels according to the rate of binder

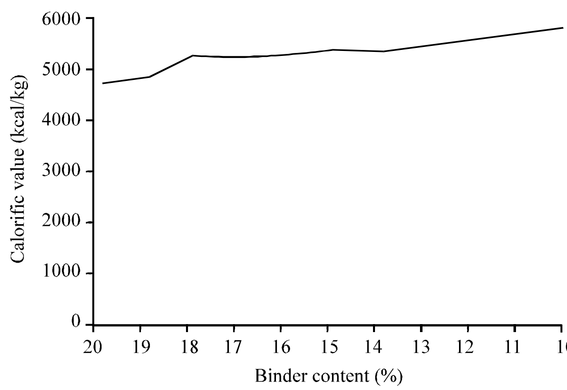

Fig. 16: Evolution of the calorific value of the biofuels of cardboard according to the binder rate

the calorific value of charcoal (reference). It has the lowest values among all types of biochar. The average value is 4580 kcal/kg.

Charcoal is known for its high calorific value (26300 kJ/kg or 6698 kcal/kg). The calorific value of charcoal can vary by ±2000 kJ/kg depending on the type of wood used. This is due to the presence of different species, the non-homogeneous quality of carbonization, the presence of bark and branches.

Waste coals all have Calorific Values (CV) close to that of charcoal except cardboard which has a slightly lower one. Waste coal humidity has an impact on the calorific value. Clay is a mineral compound but is not considered as a fuel. This reduces the calorific value which decreases when increasing the rate of binder (clay). The alternative fuels (biochar) produced from waste, thus, have calorific values satisfactory for domestic use.

Density: Table 6 shows the results of the densities of biofuels. Charcoal (reference) has a density of 425 kg/m^3 which may vary depending on the density of the wood

Table 6: Density of waste coals

Type of waste	g/L or kg/m^3
Textiles and sanitary textiles	822.2
Unclassified fuels	1101.4
Paper	954
Cardboard	948.1
Wood	600.91
Charcoal (Reference)	424.56

species used. Waste coals are denser than charcoal with densities around 600-1100 kg/m^3 (Table 6). This means that time of consumption is less important for biofuels. These results were confirmed by boiling tests during which we noted a faster burning time with the charcoal reference.

CONCLUSION

In the current context of increasing waste generation, alternative fuel formulation is emerging as a future solution for waste treatment in a spirit of sustainable development. For this study, we carried out a characterization campaign (collection and sorting) which made it possible to know the composition and the flow of household waste and assimilated in the region of Dakar, and to see the methods of energy valorization possible in this case the production of biofuels. The experimental phase and the monitoring of physical characteristics revealed that biofuels are good alternative fuel to charcoal. Coals made from household and similar waste have high ash content (29-70%) and heating values close to that of charcoal except for cardboard with a slightly lower calorific value. The results showed that the waste coals are denser than the charcoal (425 kg/m^3) with higher densities, thus, giving less burning time.

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