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RESEARCH ARTICLE

IDENTIFICATION OF THE OPTIMAL CHARRING TEMPERATURE AND THE MOST SUITABLE WOOD SPECIES FOR CHARCOAL PRODUCTION IN BENIN

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ABSTRACT

Charcoal is the main fuel used for domestic cooking in urban and peri-urban areas, with wood being used more often in rural areas in Benin. The quality of charcoal and the anhydrous weight yield of wood charcoal depends on several factors, including charcoal temperature and wood species. The lack of control of these data by charcoal makers in Benin causes socio-environmental and economic problems. The objective of this paper is therefore to determine the optimal charcoal temperature range and wood species best suited for optimal production of excellent quality charcoal in Benin. For this purpose, based on the physicochemical characteristics of about ten wood species, three tropical species, namely Bridelia ferruginea, Burkea africana and Prosopis africana, are selected and charred at different temperatures for a constant time. The physico-chemical characteristics of the coals obtained and the anhydrous weight yield of the carbonisation are determined in accordance with the standards in force. A Principal Component Analysis (PCA) between the calculated values allowed to potentially identify the Prosopis africana and Burkea africana species as the best for optimal coal production. The requirements of standard NF EN 1860-2 on the quality of a charcoal make it possible to identify the Prosopis africana species as the best adapted to the optimal production of quality charcoal. Prosopis africana produces charcoal with the maximum anhydrous weight yield (41.3%) at a charring temperature of approximately 400°C. The physico-chemical characteristics of the coal produced are: lower calorific value (26,82 MJ/kg), ash content (1,35 %), moisture content (6 %), fixed carbon content (78,84 %), volatile matter content (19,81 %).

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INTRODUCTION

Energy is essential to meet the vital needs of mankind. Energy for cooking and domestic heating accounts for about 70% of total energy consumption in sub-Saharan Africa (IEA, 2019). The International Energy Agency (2019) estimates that 900 million people do not have access to clean cooking, representing one third of the world's population. Nearly 95% of them use solid biomass, mainly in the form of firewood. Moreover, 80% of these people without access to clean cooking are located in rural areas. Fagbemi and al.(2020) showed that in Benin out of 506 households living in rural areas in energy poverty, fuel wood accounts for 76.48% of their total energy consumption. More than 750 million cubic metres of wood were harvested on the African continent in 2017, representing about 20% of the world total. The share of harvested wood used for energy is about 90% (2017). Furthermore, the use of fuelwood is still at the traditional stage with inefficient open fires or simple kitchen stoves resulting in significant effects on health, education and the environment. For example, 500,000 premature deaths due to smoke from inefficient and polluting stoves have been observed in sub-Saharan Africa in 2018 (IEA, 2019)). As a result, households spend an average of 1.4 hours per day collecting fuelwood, a burden borne mainly by women and children (IEA, 2017). In addition, 96.05% of households in energy poverty in Benin report suffering from respiratory and visual health problems caused by the emission of fuelwood burned in inefficient stoves (Fagbemi, 2020). In the face of these problems, some researchers have shown that charcoal is the appropriate solution. In addition, converting fuelwood into charcoal improves its calorific capacity and facilitates its transportation (Amaral, 2016; Koyuncu, 2007; Group, 2003). Thus, the manufacture and marketing of charcoal has become a source of economic income. Better still, charcoal is widely used in urban and peri-urban areas for cooking energy needs.

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As a result, charcoal provides clean combustion with fewer emissions than firewood. Sub-Saharan Africa has seen an annual increase in charcoal production at an average rate of about 4% per year since 2000 (IEA, 2019). In particular, 479 kilotonnes of charcoal were produced in 2015 in Benin, with an estimated annual increase of 2.80%. Given the importance of charcoal use for cooking in sub-Saharan Africa, the implications of charcoal use and population growth, the use of suitable wood species and improved technology would have considerable benefits. Technologically, sub-Saharan Africa is still at the stage of traditional and Casamance grindstones. Although more modern technologies exist, the standard of living of the population is not conducive to the transition. It prefers to limit itself to the few functional improvements made to millstone kilns, the most common of which is to have more canopies. As for carbonising fuels for optimal production, studies are still sketchy. The charcoal producers base their choice of carbonising fuels on their experience and feedback. In Benin, some authors show that the species:

Afzelia africana, Anogeissus leiocarpa ("African Birch"), Burkea africana, Diospyros mesiliformis, Khaya senegalensis, Pterocarpus erinaceus, Prosopis africana, Terminalia avicenioides, Vitellaria paradoxa, Bridelia ferruginea, Hymenocardia acida, Pericopsis laxiflora, Pseudocedrela kotschyi, Tectonia Grandis or Teak, Senna Siaméa, Acacia Auriculiformi are the most commonly used for coal production (Juhé-beaulaton, 2006; Akossou, 2013). *Burkea africana, Prosopis africana* and possibly *Bridelia ferruginea* have been identified as the most suitable species for charcoal production in Benin.

However, no information is available on the anhydrous weight yield and quality of coals from the three selected species. Hence the need to conduct this study to fill the knowledge gap on this subject. This paper therefore seeks to identify the most suitable wood species for charcoal production in Benin and the optimal temperature range for carbonization.

MATERIALS AND METHODS

Wood species used: This study was based on the following three wood species: Bridelia ferruginea (B1), Burkea africana (B2) and Prosopis africana (B3). They were selected among ten (10) species most used in Benin during our last study (not yet published), which focused on the physico-chemical characterization and identification of wood species in Benin with high thermal conversion for carbonization. These species, illustrated in Figure 1, have lower calorific values and high fixed carbon and then low ash and volatile matter rates.

Figure 1. Species of wood

Table 1 shows the anhydrous lower calorific values ($LCV_{bois,sec}$), the fixed carbon (FC), ash (AC) and volatile matter (VM) content of the three species Bridelia ferruginea (B1), Burkea africana (B2) and Prosopis africana (B3).

Table 1. Some physico-chemical characteristics of the three wood species

Essences	*Bridelia ferruginea* (B1)	*Burkea africana*(B2)	*Prosopis africana* (B3)
$LCV_{bois,sec}$ (MJ/kg)	17.3	19.5	19.3
FC (%)	19,94	24,90	23,85
AC (%)	0,6	1,1	0,9
VM (%)	79,48	73,93	75,27

Carbonization of wood species: Carbonization was carried out in a muffle furnace type SX-4-10. This is a laboratory furnace, used for thermal decomposition and other applications involving heating of small sample sizes. The main features are presented in Table 2.

Table 2- Characteristics of the muffle furnace SX-4-10

Characteristics	Values
Rated power	4 kW
Rated voltage	220 V
Inner Dimension	300*200*120 mm
Rated temperature	1000 °C
Maximum heating time	80 min
Accuracy	+/- 2 °C

Method used: The three wood species were treated and charred according to the following steps:

- **Step 1**: Drying of the essences

Drying consisted of eliminating the amount of free water contained in each of the species. It allowed the calculation of the anhydrous masses according to equation 1. The balance used for the measurements is a OHAUS balance with a capacity of 4000 g and an accuracy of 0,001 g.

$$m_{anh} = m_2 - m_1 \qquad (1)$$

Where,

m_1 : Mass of the empty weighing pan;
m_2 : Mass of the tray assembly + dry wood species.

The essences were dried in an oven at 105°C for about 12 hours. Their weighing and drying were repeated until a consecutive difference in mass was obtained which was less than or equal to the resolution of the balance used.

- **Step 2** : Thermal decomposition of the wood species

Table 3. Operating conditions for carbonization

Wood species	Operating conditions for carbonization	
	Time (min)	Carbonization temperatures (°C)
Bridelia ferruginea(B1)	60	350 à 650
Burkea africana(B2)		
Prosopis africana (B3)		

The dried species were charred by species category at a constant heating rate for a constant time and then non-isothermally. Table 3 shows the carbonization conditions and the various maximum temperatures reached.

The carbonization was done at temperatures in the closed range (350; 650)°C with a subdivision step of 50°C. This range was used because roasting generally extends from 200 to 300°C; pyrolysis covers about 350 to 700°C; and gasification from about 800°C upwards (10).

Expression of the anhydrous weight yield of carbonization: The anhydrous weight yield (r in %) is calculated according to equation 2.

$$r = \frac{m_c}{m_{anh}} * 100 \qquad (2)$$

Where,

m_c : Mass of charcoal; measured after cooling (in grams);
m_{anh} :Anhydrous mass of the wood species (in grams).

Expression of carbonization energy yield: The energy yield of carbonization is the ratio between the potential heat energy of the coal produced and the potential heat energy of the wood species initially used. The equation 3 is used to calculate this efficiency.

$$\eta = (100 * m_c * LCV_{sec})/(m_{anh} * LCV_{bois,sec}) \qquad (3)$$

Where,

LCV_{sec} : Anhydrous net calorific value of coal produced.

Experimental determination of physico-chemical characteristics: The physico-chemical characteristics determined in this study are the moisture content (h), calorific value, volatile matter content (%V), ash content (%A) and fixed carbon content (%C_{fixed}) of the coals produced. They have been determined in accordance with the standards in vigour.

Moisture content (h): The determination of moisture content consists of drying the coal at 105°C to remove the free water it contains. It has been evaluated in accordance with standard NF EN ISO 18134-3. Equation 4 allows the calculation of the moisture content (hen %).

$$h = \frac{m_2 - m_3}{m_2 - m_1} * 100 \qquad (4)$$

Where,

m_1 : Mass of the empty weighing pan (in grams);
m_2 : Mass of the pan + test sample (in grams);
m_3: Constant mass obtained after drying of the tray + test sample (in grams).

Pouvoir calorifique: Calorific value is the amount of energy contained in a unit of mass of fuel. A distinction is made between HCV (Higher Calorific Value) and LCV (Lower Calorific Value). The experimental determination of HCV is made according to the NF EN ISO 18125 : 2017 standard. The LCV is calculated from the measured HCV. The lower calorific value is the energy theoretically recoverable by the user. This is the most interesting data to use. In this study, the PCS measurements are carried out in the PARR 6100 type calorimetric bomb. The apparatus is calibrated with a benzoic acid pellet. The mass of water is thus determined (calorimeter bomb and calorimeter). The calorimeter canister is then charged with oxygen at a pressure of 25 bar. The sample is placed in a dish 25 mm in diameter and 14 to 19 mm high before being inserted into the canister immersed in a calorimeter vessel. Combustion is triggered electrically by a wire. The water temperature is monitored every thirty (30) seconds before and after combustion until a linear cooling regime is reached. The gross calorific value (HCV in J/g) is calculated and displayed directly, however the following equation 5 is the one that allows this calculation.

$$HCV = \frac{K_1 * E_{cal} * (t_m - t_i) - K_1 * (L - l) * E_{pt}}{M} \qquad (5)$$

E_{cal}: Calorimetric equivalent of the calorimeter, the bomb, their accessories and the water introduced into the bomb ($E_{cal}$is calculated by making at least 5 corresponding determinations of the HCV of benzoic acid of "calorimeter standard" quality), $E_{cal}$is expressed in Cal/°C (determine regularly, take the average) ; E_{pt} : calorific value of platinum 2,3 cal/cm ; K_1 : calorie conversion factor in Joules = 4,185 5 J/Cal ;t_m : maximum temperature in °C; t_i: initial temperature in °C ; L : initial length of the platinum filament in cm ; l: remaining length of the platinum filament in cm ; M : mass of the sample to be analysed in g.

Therefore, the gross calorific value on dry basis (HCV_{sec}) is determined by equation 6.

$$HCV_{sec} = HCV * \frac{100}{100 - h} \qquad (6)$$

The lower heating value on dry matter ($LCV_{sec} enJ/g$), calculated according to equation 7.

$$LCV_{sec} = LCV_{sec} - 25{,}1 * h_2 \qquad (7)$$

With,

$$h_2 = 8\,937 * H * \frac{100 - h}{100} + h \qquad (8)$$

Where, H: Mass content of hydrogen.

Volatile content (%V): Volatile matter contained in coal includes condensable gas residues that have not been removed during carbonization. A charcoal with a high volatile content will burn with a smoky flame, while a charcoal with a low volatile content will be difficult to ignite but will burn with a clear flame. Thus, a good quality charcoal should have a low volatile content. In this work, the volatile matter content is calculated according to the NF EN ISO 18123 standard. It is calculated according to the equation 10.

$$\% V = \left[\frac{m_2 - m_3}{m_2 - m_1} * 100 - h\right] * \frac{100}{100 - h} \qquad (9)$$

Where,

h : Moisture content;
m_1: Mass of the balance pan;
m_2: Mass of sample (approx. 1g) + cover;
m_3: Mass of the sample + cover previously introduced into the oven, which has already been heated to 900°C for 7 min +/- 5 s and then cooled to room temperature.

Ash content (%A): Ash is composed of mineral matter originally present in wood species. Assessing the ash content is essential because it affects the quality of the coal. It is obtained after incineration in a muffle furnace at a specified heating regime, up to a temperature of 815°C +/- 10°C and maintained at this temperature until a constant mass of ash is obtained. The ash content has been determined in accordance with standard NF EN ISO 18122. Equation 10 allows to calculate the ash content on the dry matter.

$$\% A = \frac{m_3 - m_1}{m_2 - m_1} * 100 * \frac{100}{100 - h} \qquad (10)$$

Where,

m_1: Mass of the weighing pan in grams;
m_2: Mass of the weighing pan + sample in grams;
m_3: Mass of the pan + cooled ash in grams;
h: Moisture content of the dry sample.

Fixed carbon rate ($\%C_{fixed}$)

The fixed carbon content of charcoal is an important element determining its quality. The higher the carbonization temperature, the higher the fixed carbon content of the charcoal. The fixed carbon content of charcoal was determined according to equation 11.

$$C_{fixed} = 100 - (\%V + \% A) \qquad (11)$$

RESULTS AND DISCUSSION

Results

Anhydrous weight yields: Figure 2 illustrates the coals produced by carbonization of the wood species studied. In this figure, codes C1, C2 and C3 refer to coals from *Bridelia ferruginea*, *Burkea africana* and *Prosopis africana*, respectively. In addition, Figure 3 shows the evolution of the anhydrous weight yield as a function of the carbonization temperatures of each of the coals C1, C2 and C3, respectively.

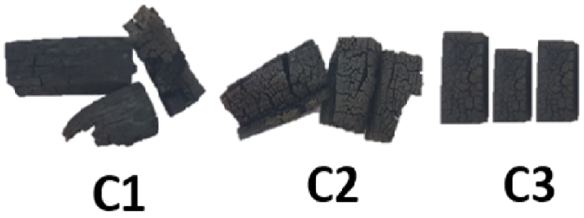

Figure 2. Carbonized species coals

This figure shows that, for all coals C1, C2 and C3, the anhydrous weight yield is a function with an overall maximum over the set of defined temperatures. Indeed, the C1 coal of Bridelia ferruginea essence After this temperature, the efficiency decreases. As for the curve of C2 coal of *Burkea africana*essence, the efficiency reaches two peaks. The first of 34.55% is obtained at 350°C and the second of 28.67% at 550°C. Similarly, *Prosopis africana*essence's C3 coal yield curve also has two peaks, 41.3% at 400°C and 35.9% at 600°C. In addition, comparing the three curves in Figure 3, we observe that over the entire range of 400-550°C, C3 coal has the highest anhydrous weight yield. Its maximum value is 41.3% at 400°C. In contrast, at a temperature of 350°C, *Bridelia ferrugine* coal C1 has the highest coal yield relative to C2, but less than that of C3.

On average, the anhydrous weight efficiencies of C1, C2 and C3 coals are 30.10%, 29% and 36.87% respectively.

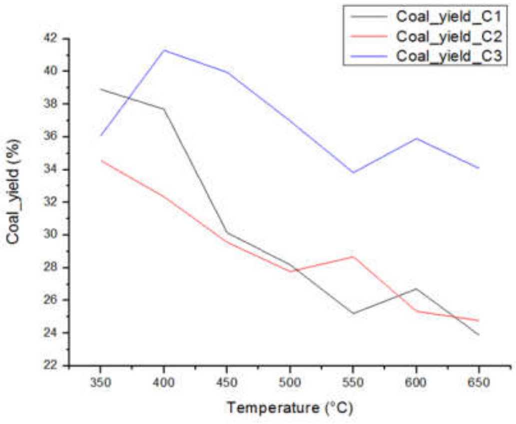

Figure 3- Temperature-dependent anhydrous weight yield

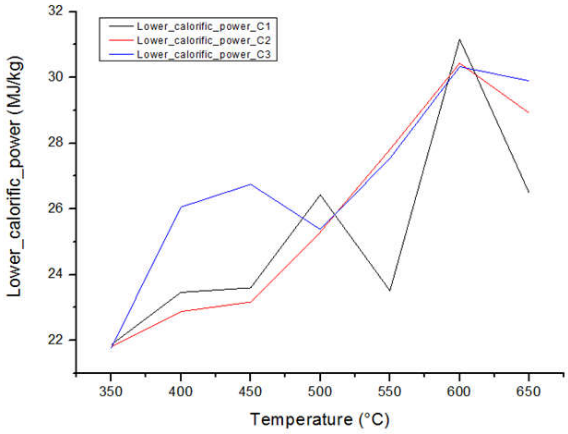

Figure 4. Lower calorific value as a function of carbonization temperature

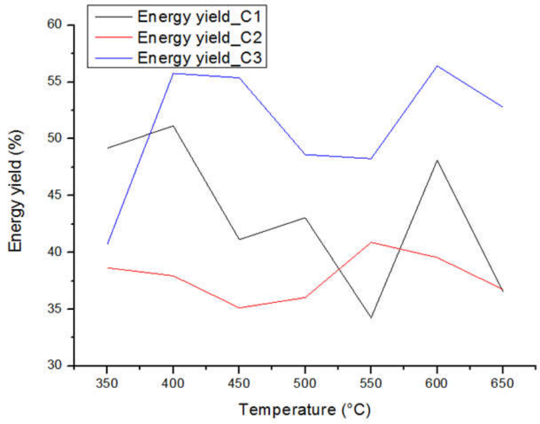

Figure 5. Energy yield of coals

Table 4- Physico-chemical characteristics of the coals obtained

	C1	C2	C3
Fixed carbon rate (%)	77,10	78,71	78,84
Volatile matter content (%)	19,56	19,82	19,81
Moisture content (%)	8,59	7,53	6
Ash content (%)	3,33	1,47	1,35

Physico-chemical characteristics of carbonised species

Lower calorific value (LCV): Figure 4 illustrates the evolution of the lower calorific values of coals C1, C2 and C3 as a function of temperature.

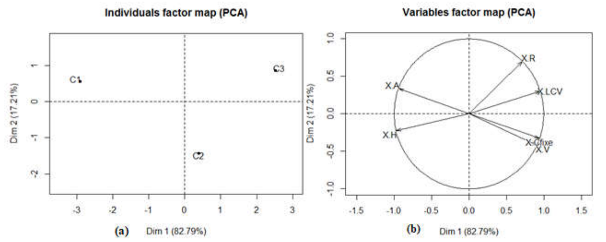

Figure 6. Principal Component Analysis of Coal Characteristics

Looking at the temperature range where the maximum carbonisation efficiencies were obtained, i.e. from 350°C to about 475°C, the lower calorific value of *Prosopis africana*essence C3 coal is the highest. It reaches a maximum of about 26.75 MJ/kg at 450°C. On average, the LCVs of C1, C2 and C3 coals are 25.22 MJ/kg, 25.76 MJ/kg and 26.82 MJ/kg, respectively.

Other physico-chemical characteristics: Table 4 shows the average values for the following characteristics: fixed carbon content, volatile matter content, moisture content and ash content. This table shows that only C3 coal has the highest fixed carbon content (78.84%), moisture content (6 %) and ash content (1.35%). It should be noted that there is no significant difference in volatile matter content. Carbonization energy yields: Figure 5 illustrates the energy efficiency as a function of the carbonization temperatures of each of the coals C1, C2 and C3, respectively. This figure shows that over virtually the entire charring temperature range (400°C to 650°C), the coal (C3) in *Prosopis africana* essence has the highest production energy yield. For charring temperatures of 400°C and 600°C, C3 coal is produced with maximum energy efficiencies of 55.76% and 56.41%, respectively.

DISCUSSION

A coal is of quality when it possesses certain interesting physico-chemical characteristics, including a lower calorific value (LCV) and a high fixed carbon content (% Cfixe), then an ash content (% A) and a low moisture content (X.H). In addition to quality, high anhydrous carbonization weight yields (r) are desired. Therefore, a statistical analysis in main components carried out on all physico-chemical characteristics and the calculated anhydrous weight yields give the curves in Figure 6. The axes dim1 and dim 2 represent the correlation between all the physico-chemical characteristics and the yields analysed. The figure shows that the inertias 17.21% for axis 2 and 82.79% for axis 1 prove that the two axes are sufficient to interpret the relationships between the types of coals, the physico-chemical characteristics and yields. Curve (a) in Figure 6 shows that coal C2 is negatively correlated with axis 1 while coals C3 and C1 are positively and negatively correlated with axis 2 respectively. Consequently, curve b of the same figure shows that the ash (X.A) and moisture (X.H) contents are negatively correlated with axis 2 while all other physico-chemical characteristics and yield are positively correlated with this axis. On the one hand, we deduce that the C3 coal of *Prosopis africana*essence has a high lower calorific value (X.LCV) and a high anhydrous weight yield (X.R). On the other hand, the C2 coal of *Burkea africana*essence has a high fixed carbon content and the *Bridelia ferrugine*essence results in a C3 coal with a low yield and LCV and then with high centre and moisture content. Therefore from the principal component analysis, the two species to be selected are *Prosopis africana* and possibly *Burkea africana*.

In addition, standard NF EN 1860-2 specifies certain technical constraints relating to the quality of a coal. It recommends a fixed carbon content greater than or equal to 78 %, an ash content less than or equal to 6 % and a moisture content not exceeding 6 %. Of the two essences selected for principal component analysis, only the C3 coal of *Prosopisafricana* essence complies with the listed normative requirements. Since the best species is thus identified, we can carbonise it over the temperature range 400°C to 650°C, where the carbonisation energy yield is high. More specifically, at a charring temperature of 400°C, the anhydrous weight yield of Prosopis africana essence is maximum (41.3%). This yield value is higher than that found by Akossou and al. (9) in their study of the wood charring technique in northwest Benin. These authors estimate the anhydrous weight yield of Prosopis africana charring at 37.55%. This difference from the yield value found in this article can be explained by the traditional technology used by charcoal makers, for which temperature fluctuations are noted. Furthermore, from carbonization temperatures of 500°C, the anhydrous coal yield of the selected essence decreases. This can be explained by the onset of secondary carbonisation mechanisms. This observation was also made by Fagbemi and al. (2001) during their study on the evaluation of the quantities of different pyrolysis products of three biomasses (wood, coconut shells and straw). These authors showed that at temperatures above 600°C, secondary reactions carry off and lead to a reduction in charcoal weight yield (11).

Conclusion

The species *Bridelia ferruginea* and *Prosopis africana* are suitable for carbonization in Benin. The *Prosopis africana* essence is best suited for the optimal production of quality charcoal. Its carbonisation gives a maximum anhydrous weight yield of 41.3% at a temperature of 400°C. The coal produced is of high quality, as the values of its physico-chemical characteristics comply with the constraints of standard NF EN 1860-2. As for the coals produced from *Bridelia ferruginea*, *Burkea africana*, the values of their physico-chemical characteristics lead to the conclusion that they are of lower quality. Nevertheless, coal from *Bridelia ferrug*inea is produced with a maximum yield of 38,91 % at temperature of 350 °C. At the end of this study, we recommend that charcoal makers in Benin use *Prosopis africana* wood species at a charring temperature of about 400°C. At the same time, a reforestation policy should be implemented to make this species available throughout the country and to ensure its continued existence. The other species could be used to a lesser extent while ensuring reforestation. Charcoal production centres that do not have *Prosopis africana* in their locality could resort to charcoal production from the other two species to a lesser extent.

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