Physico-chemical Characterization and Identification of Wood Species in Benin with High Bio-thermal Conversion for Carbonization

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Authors' contributions

*This work was carried out in collaboration among all authors. Author GG designed the study,
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Original Research Article

ABSTRACT

Physico-chemical characteristics of ten tropical wood species in Benin were determined to identify
the species with high bio-thermal conversion for carbonization (charcoal production). The wood
species were obtained from Dassa-Zoume, Dan, and Djidja localities in Central region, where
charcoal production is a major economic activity. The physico-chemical properties determined were
elemental composition, fixed carbon content, volatile matter content, ash content, and calorific
value. The species selection criteria was quantified using Principal Component Analysis (PCA)
statistical method implemented by R-software package. The three wood species identified as most
suitable for bio-thermal conversion were *Burkea africana* (Wild Syringa), *Prosopis africana*
(Mesquite Iron Tree) and *Bridelia ferruginea* (Bridelia Yellow Cassia), which exhibited high calorific
values, high fixed carbon levels and relatively low proportions of ash and volatile matter.

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1. INTRODUCTION

Access to sustainable energy is a major challenge for rural communities in Sub-Sahara Africa, as the population relies mostly on biomass in the form of fuel wood and charcoal as the main source of energy. In Benin, the main route for biomass thermal conversion is carbonization process, which is characterized by low efficiency, low mass yield (less than 15%) and poor quality of charcoal produced, since the production system is artisanal and rudimentary with low carbonization yields of 8 - 15%. As common practice, any available wood specie is carbonized without any scientific or technical appraisal of suitability of the specie for the bio-thermal conversion. There is also competition between charcoal producers and other commercial wood users, leading to over exploitation, species extinction and deforestation [1].

Carbonization efficiency and quality of charcoal produced are related to the nature of the wood species, especially the physico-chemical properties of calorific value, ash content, volatile matter content, fixed carbon content, density and elementary composition; which characterize and identify the most suitable of species for carbonization [1-4]. Commercial charcoal production for domestic and industrial purposes in Benin accelerate deforestation [5], and for sustainable production, selection of suitable wood species would ensure both environmental and forest resources conservation and management.

Wood consists of three basic polymers; cellulose $(C_6H_{10}O_5)_n$, hemicellulose (such as xylen $(C_5H_8O_4)_m$), and lignin $[C_9H_{10}O_3 (OC H_3)_{0.9-1.7}]_x$, in addition of extractives and minerals [3]. Hardwoods have higher proportion of cellulose, hemicellulose and extractives than softwood. Thermal degradation or bio-thermal conversion of wood in absence of oxygen results in production of charcoal (solid) [6].

Combustion, gasification and pyrolysis are the three main thermal processes of converting wood into various energy products. Pyrolysis is thermal destruction of biomass in absence of air or oxygen to produce charcoal, syngas and liquid bio-oil. Carbonization is a slow pyrolysis process in which wood is converted into charcoal, by heating the wood in an oxygen free or oxygen limited environment and reaction conditions to maximize production of charcoal [6].

For efficient production of charcoal in Benin, with high energy yields and quality characteristics, research was conducted to identify wood species most suitable for carbonization. Several parameters are determined. Among them calorific value, ash or mineral content, fixed carbon content, volatile matter content, moisture content, and elemental compositional analysis. These characteristics are analyzed by PCA method to identify wood species suitability for charcoal production [7].

2. METHODOLOGY

2.1 Selection of Wood Species

Based on in-depth bibliographic review of wood resources and charcoal production systems in Benin [8], ten wood species selected for carbonization studies were *Hymenocardia acida* (Heart fruit), *Pericopsis laxiflora* (Aframosia or Africa teak), *Terminalia avicenioides* (Bamabara), *Khaya senegalensis* (Mahogany), *Burkea africana* (Wild syringa), *Prosopis africcana* (Mesquite iron tree), *Vitellaria paradox* (Shea butter tree), *Anogeissus leiocarpa (*African birch), *Bridelia ferruginea* (Bridelia yellow cassia), and *Senna siaméa* (Cassia tree). The species were collected from Central Region, in the localities of Dassa-Zoume, Dan, and Djidja, where the species were abundant in the main centers of charcoal production [8].

Table 1 lists the wood species, sources in Benin, availability, density, hard or softwood and IUCN status on vulnerability, with Coding B1 to B10. The maturity or ages of the species were not be estimated

2.2 Experimental Measurements of Physico-chemical Properties

The wood species were characterized at Agricultural Research Development Laboratory of the Centre for International Cooperation (CIRAD) in Montpelier, France. The physico-chemical properties were determined using International Standards of measurements, such as ASTM[1], for moisture content, ash content,

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[1]*American Society for Testing Material*

Table 1. Common wood species used for charcoal production in Benin

Code No.	Scientific Names	Common Names	Location	Vernacular Names	(IUCN[2]) Status	Air Dry Density (g/cm^3) [5, 6, 7]	Availability (High, medium, low)	Hard (H) or Soft (S) wood
B1	*Hymenocardia acida*	Heart fruit	Zouzounkan - collines and throughout the north	Sotinvè (in Fongbé) & orupa (in Yoruba)	Minor concern	0.91 – 1.01	Medium	H
B2	*Pericopsis laxiflora*	Afromosia/ Africa teak	Zouzounkan - collines and throughout the north	Sindon (in Fongbé)	Minor concern	0.62 – 0.80	High	H
B3	*Terminalia avicenioides*	Bambara	FC Lama -Zuzounkan - collines and throughout the north	Dagossilo (in Fongbé) or Allotoun	Minor concern	0.80 – 0.90	Medium	H
B4	*Khaya senegalensis*	Mahagony	From South to North	Zounza, Acajou (in Fongbé)	Endangered species	0.67 – 0.90	Medium	H
B5	*Burkea africana*	Wild syringa	Zouzounkan -collines and throughout the north	Avigo orAdjassikakè (in Fongbé)	Minor concern	0.73 – 1.14	High	H
B6	*Prosopis africana*	Mesquite iron tree	FC Lama Zouzounkan - collines and throughout the north	Kakè (in Fongbé)	Vulnerable	0.0.91 – 1.04	Medium	H
B7	*Vitellaria paradoxa*	Shea butter tree	Zouzounkan - collines and throughout the north	Wougo, kotoblè or limoutin (in Fongbé)	Vulnerable	0.72	Medium	H
B8	*Anogeissus leiocarpus*	African Birch	FC Lama Zouzounkan -collines and throughout the north	Hlinhon (in Fongbé)	Near threatened	0.78 – 0.79	Medium	H
B9	*Bridelia ferruginea*	Bridelia Yellow	FC Lama Zouzounkan - collines and throughout the north	Honsoukouék oué (in Fongbé)	Minor concern	0.51 – 0.64	Medium	H
B10	*Senna siaméa*	Cassia	FC Lama Zouzounkan - collines and throughout the north	Kenu (in Fongbé)	Minor concern	0.59	Medium	H

Dry density determined at 12% moisture content

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[2]*IUCN International Union for Conservation of Nature*

volatile matter content, fixed carbon content and calorific value. The wood samples were conditioned by crushing into powder particles passing 1 mm opening sieve, at IKA Mill Laboratory 27 MOS2-027, in addition to small-sized rectangular shapes.

2.2.1 Elemental compositional

The elemental compositions of the species, Carbon, Hydrogen, Oxygen and Nitrogen, were determined as part of the ultimate analysis according to International Standard ASTM D53 73 and NF EN ISO 16948, and the data was used to calculate the energy content and gaseous emission potentials of the wood.

2.2.2 Moisture content

The moisture content was determined as the amount of free water in the wood specie removed by drying at 105°C, according to the International Standard AFNOR NF EN ISO 18 134-3. A small-sized rectangular shaped wood sample was dried in an electric oven at 105°C and maintained at the temperature until a constant mass was obtained. The moisture content, H, was calculated from mass lost of the sample, and expressed as percentage (dry basis), according to equation (1)

$$H = \left(\frac{m_2 - m_3}{m_2 - m_1}\right) * 100 \qquad (1)$$

where m_1 was mass of empty container for the sample (g), m_2 was mass of container with sample before putting in the oven (g), m_3 was mass of container with the sample after drying in the oven (g). Several measurements were made for each sample to obtain average values of the masses, measured to error of less than 5.0%.

2.2.3 Ash content

The ash content was determined as residue from the species after heating in air to 550°C. The parameter is of paramount importance in bio-thermal conversion process, and determines efficiency of carbonization process and quality of charcoal produced. An empty capsule was weighed to the nearest 0.1 mg (mass m_1), then 1 to 2 g of the powdered wood sample was uniformly spread in the capsule and weighed (mass m_2). The ash content was determined using International standard NF EN ISO 18122.

The capsule and contents were introduced into the muffle furnace at room temperature, and the preset program P1 (MOS2-028) was initiated, consisting of raising the temperature to 250°C in

50 min, maintaining for 60 min, then increasing the furnace temperature from 250°C to 550°C in 60 min and maintaining at the temperature until a constant mass was attained after about 2 hours of firing. The capsule and contents were taken out of the oven, placed on insulating plate to cool for 5 to 10 minutes, then placed in a desiccator to attain room temperature, and weighed to nearest 0.1 mg (m_3).

The ash content were calculated using equation (2),

$$\% \ (A) = \left(\frac{m_3 - m_1}{m_2 - m_1}\right) * 100 * \left(\frac{100}{100 - H}\right) \qquad (2)$$

where H% was moisture content of the sample. The average% Ash Content from a number of trials were calculated to the nearest 5.0%.

2.2.4 Volatile matter content

The volatile matter content was determined by mass loss deducted from the moisture loss when the wood sample was heated without air at standard atmospheric conditions. The parameter was key to identifying wood species producing quality charcoal by carbonization, as species with high volatile matter produced low quality charcoal.

The volatile matter content was determined in accordance with International standard NF EN ISO 18123. An empty crucible with cover was weighed (mass m1), and 1 g ± 0.1 g of wood sample (mass m2) put in to the crucible. When the furnace attained constant temperature of 900°C, the crucible and wood contents were introduced into the furnace, left inside the furnace for 7 min ± 5 s, and later removed to cool for 10 minutes on insulating plate, and then placed in a desiccator to attain room temperature, and weighed to the nearest 0.1 mg (mass m3).

The volatile matter content was determined from equation 3,

$$V = \left(\frac{m_2 - m_3}{m_2 - m_1}\right)(100 - H)\left(\frac{100}{100 - H}\right) \qquad (3)$$

where H% was moisture content of wood sample. The average value of V was obtained from a number of experimental trials, at error of less than 5%.

2.2.5 Fixed carbon content

Fixed carbon was amount of carbon in wood after removal of volatile matter and ash, and the

parameter affirmed choice of species, as higher fixed carbon content denoted quality and energy properties of the wood. The percentage of fixed carbon was determined in accordance with International standards NF EN ISO 18123 and ISO1213-2, using equation 4,

$$C_{fixed} = 100 - (V + A) \qquad (4)$$

where V was volatile matter content and A was ash content (all as% mass of dry wood), calculated to less than 5% experimental error.

2.2.6 Calorific values

During bio-thermal conversion or carbonization, the wood was not oven dried when burnt and water in the wood was evaporated, reducing the extractable energy to a net calorific value or lower calorific value (LCV) on wet basis or anhydrous condition, whereby the latent heat of vaporization of water created by combustion was not recovered by condensation. Oven dry wood has calorific value on dry basis given as gross calorific value or high calorific value (HCV).

The calorific value of wood sample was energy content determined from the moisture and hydrogen content of the sample, according to the NF EN ISO 18125 standard. The wood was burnt in presence of high-pressure oxygen in a bomb calorimeter. The HCV at constant volume was calculated from increase in temperature of water contained in the calorimeter, taking into account secondary chemical reactions and possible heat losses. The LCV was then determined from HCV. A minimum of 2 tests per sample was required.

The instrument setup estimated HCV directly from data entered during the experiment. A formula for calculation HCV was

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

where E_{cal} (Cal/°C) was calorimetric equivalent of the bomb calorimeter, accessories and water input, determined from average determination of HCV of benzoic acid of standard quality, E_{pt} was calorific value of platinum (2.3 cal/cm), K_1 was calorie conversion factor (4.1855 J/Cal), t_m was maximum temperature, t_i was initial temperature, L was initial platinum wire length (cm), ℓ was remaining platinum wire length (cm), and M was mass of wood sample combusted (g).

2.3 Data Analysis

2.3.1 Principal Component Analysis (PCA)

Principal Component Analysis (PCA) was multivariate statistical tool adopted for transforming interrelated (correlated) variables into new variables that were uncorrelated with each other. For n individuals observed on p quantitative variables, PCA established links between variables and similarities between individuals, and hence defined k new variables of linear combinations of the initial p variables that caused the least amount of information to be lost.

The variables were principal components, the axes were principal axes of associated linear forms of principal factors [9].

For p quantitative variables, $X^1, \dots, X^j, \dots, X^p$, observed on n individuals, $1, \dots, \dots, \dots, n$, the observation of the variable X^j on individual i, $X^j(i)$, was denoted by X_i^j. The data was presented in array from. The number p of variables was at least 2, and the number n of individuals was at least equal to p. The information from the data was extracted to make graphical representations of the initial data, convenient for interpretation.

Data was centered and reduced, if the units of measurement of the variables were different from one variable to another. If data centering did not change the shape of the cloud, or alter the results of PCA, then

$$X_i^j = \frac{x_i^j - \overline{x^j}}{S^j} \qquad (6)$$

$$\overline{x^j} = \frac{1}{n}\sum_{i=1}^{n} x_i^j \qquad (7)$$

$$S^j = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(x_i^j - \overline{x^j}\right)^2} \qquad (8)$$

Linear combinations of initial variables (factors or principal components) sought were in the form,

$$C^1 = a_1^1 X^1 + a_1^2 X^2 + \cdots + a_1^p X^p \qquad (9)$$

$$C^2 = a_2^1 X^1 + a_2^2 X^2 + \cdots + a_2^p X^p \qquad (10)$$

etc., such that C^1 contained as much information as possible, i.e. spread individuals as widely as possible. Therefore for a cloud of points in the plane (dimension $p = 2$) projected on a straight line (dimension $q = 1$), the representative

straight line of the initial configuration made maximum dispersion, the variance of the cloud after projection. The constraint added for efficient PCA were,

$$\sum_{j=1}^{p}(a_1^j)^2 = 1 \qquad (11)$$

$$\sum_{j=1}^{p}(a_2^j)^2 = 1 \qquad (12)$$

2.3.2 R software package

The PCA was implemented using R software package, by applying the analysis method to the initial data on the physico-chemical properties of the wood species.

The R-algorithm developed and implemented for the PCA data analysis was:

```
data_acp=read.table("clipboard",header=T,dec="
",row.names=1)
attach(data_acp)
library(FactoMineR)
res_acp=PCA(data_acp)
dimdesc(res_acp)
```

3. RESULTS AND DISCUSSION

3.1 Physico-chemical Parameters

The physico-chemical characteristics of the wood species are shown in Tables 2, 3 and 4. Despite the variability, values of moisture content were used in calculating the other para-meters based on equations. (2, 3, 4, 5). The selection of most suitable wood species for carbonization by bio-thermal conversion was based on criteria relating to the critical values of the physico-chemical properties of fixed carbon content, lower calorific value, ash content and volatile matter content. The best wood specie for charcoal production exhibited very high lower calorific value, high fixed carbon content, very low ash content and volatile matter content composed of hydrogen, oxygen and carbon, transformed into steam and a mixture of hydrocarbons [10].

A wood specie with high lower calorific value, high carbon content and low ash content is most suitable for carbonization for charcoal production, [11]. From Tables 2 and 4, no specific wood specie exhibited correlation between low ash content, high Lower calorific value (LCV), and high fixed carbon content to merit selection.

Therefore, PCA was performed on the data to identify the suitable wood species.

3.2 Selection of Wood Species for Carbonization

PCA method established correlations between the wood species and physico-chemical characteristics in order to identify the species most suited for bio-thermal conversion. The PCA results obtained by R software related Dimension 1 (Dim1) of linear combination of variables fixed carbon rate and lower calorific value and Dimension 2 (Dim2) of linear combination of variables ash rate and volatile matter, as shown in R compiler output in.

The first component (Dim1) indicated 55.73% of the baseline information on the physico-chemical characteristics of the wood species on dry matter were contained in the initial variables. The first two components together indicated about 95.4% of the same information. The lower calorific value and fixed carbon content strongly positively correlated with Dim1. The rate of volatile matter and rate of ash strongly correlated with Dim 2. The rate of volatile matter positively correlated with Dim 2, while the rate of ash negatively correlated with Dim2.

The selection of suitable wood species for carbonization was based on relating the PCA analysis to the fact that the best wood species for bio-thermal conversion process had high low calorific values and fixed carbon contents with low ash and volatile matter levels.

In Fig. 1(a), species B5 and B6 were strongly positively correlated with Dim1, while species B8 was strongly negatively correlated with Dim1, i.e. samples B5 and B6 had high lower calorific values (LCV) and high fixed carbon contents, while species B8 had low LCV and fixed carbon contents. Species B4, B1 and B10 correlated positively with Dim2, while specie B7 was strongly negatively correlated with Dim 2, i.e. samples B4, B1 and B10 had high levels of volatile matter, while sample B7 had high levels of ash content. With regards to calorific value and fixed carbon content, the wood species distinguished were B5, B6, and perhaps B9. Table 5 shows comparisons of the physico-chemical parameters with reference data of species exhibiting low scores for volatile matter content and ash content, despite the data not exhibiting the lowest values [12-15].

Table 2. Immediate analysis of selected wood species based on dry density

Physico-Chemical Characteristics	Wood Species									
	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
Moisture Content (%)	8 ± 0.1	9.9 ± 0.1	12.0 ± 0.1	8.0± 0.1	24.0 ± 0.1	24.9 ± 0.1	17.0 ± 0.1	12.0 ± 0.1	10.2 ± 0.1	9.0 ± 0.1
AshContent (%) [a]	0.6 ± 0.1	3.1 ± 0.1	3.8 ± 0.1	2.2 ± 0.1	1.1 ± 0.1	0.9 ± 0.1	6.2 ± 0.1	5.3 ± 0.1	2.3 ± 0.1	2.3 ± 0.1
Volatiles Material Content (%) [a]	79.48 ± 0.08	75.99 ± 0.08	75.29 ± 0.07	79.08 ± 0.08	73.93 ± 0.07	75.27 ± 0.08	71.82 ± 0.07	76.66 ± 0.08	74.51 ± 0.08	79.65 ± 0.08
Fixed carbon content (%) [b]	19.94 ± 0.02	20.93 ± 0.02	20.9 ± 0.02	18.68 ± 0.02	24.90 ± 0.02	23.85 ± 0.02	21.98 ± 0.02	18.07 ± 0.02	23.22 ± 0.02	18.06 ± 0.09

a On dry matter, b By difference

Table 3. Proximate or ultimate analysis of wood species based on dry matter

Elemental Composition (%)	Wood Species									
	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
C [a]	48.9	48.3	48.7	49.2	53.54	52.7	49.1	45.8	48.5	46.5
H [a]	5.93	5.45	5.34	5.46	5.97	5.85	5.33	5.38	5.13	5.3
O [b]	44.95	45.46	45.64	45.29	39.74	40.72	45.00	48.45	46.17	47.4
N [a]	0.21	0.76	0.34	0.05	0.75	0.73	0.56	0.33	0.23	0.8

a On dry matter, b By difference

Table 4. Lower Calorific Value (LCV) of selected wood species

Calorific Values (MJ/kg)	Wood Species									
	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
Anhydrous LowerCalorific Value	18.2	17.7	17.8	18.2	19.5	19.3	17.7	16.2	17.3	17.1

Table 5. Comparison of physico-chemical characteristics of selected wood species

| Order of selection of wood species	Moisture content (%)	Ash rate (%)	Volatile matter content (%)	Fixed carbon rate (%)	LCV MJ/kg	Data comparison
B4 (*Khaya senegalensis*)	8.0	2.20	79,08	18.63	18.2	Present Study
	10.0	0.96	69.68	29.64	20.6	Reference [12]
B8 (*Anogeissus leiocarpus*)	7.6	2.60	35.25	62.15	21.2	Present Study
	12.0	5.30	76.66	67.00	16.2	Reference [12]
B10 (*Senna siaméa*)	10.6	1.08	62.41	36.51	18.67	Present Study
	9.0	2.30	79.65	18.06	17.1	Reference [12]
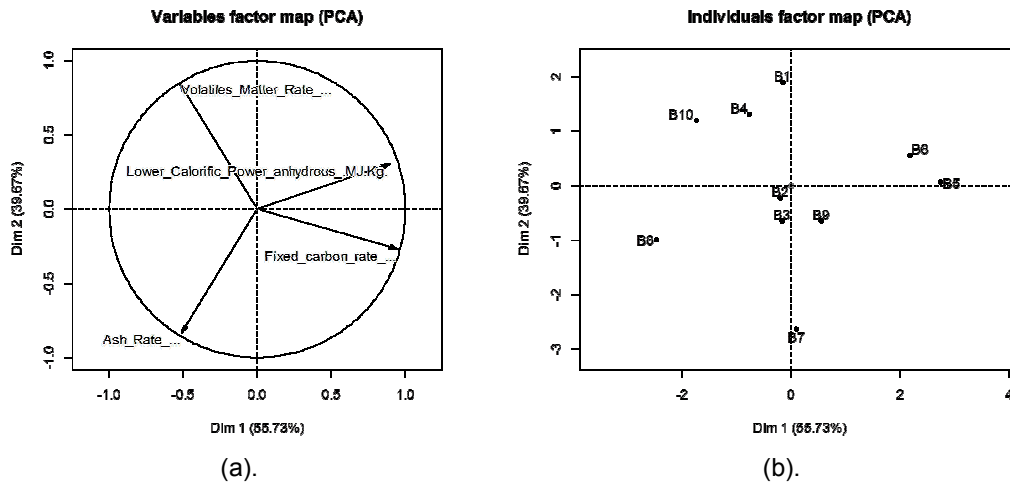
Fig. 1. Principal component analysis plots (a). variables factor map, (b). individual factor map

The correlated data of calorific value and fixed carbon content matched with volatile matter content and ash content provided criteria for selection of primary species B5 (*Burkea africana*) and B6 (*Prosopis africana*), and possibly B9 (*Bridelia ferruginea*) as the most suitable wood species in Benin for bio-thermal conversion of carbonization process. In addition, three other secondary selections of less suitability were B4, B8 and B10. Samples B1, B2, B3 and B7 are not selected because of the poor scores recorded for all the characteristics studied. Indeed, they are species that either have high volatile matter content (B1), high ash content (B7 and B8) or low or very average scores for the other characteristics determined (B2 and B3) etc. and the PCR method used does not identify them as being indexed for charcoal production in view of their characteristics which are mainly related to the nature of the wood. The selections were confirmed by previous findings [16], which indicated the species were the most commonly used for charcoal production in Benin.

3.3 Discussion

Calorific values were negatively related to ash contents, i.e., higher the ash content of fuels, the lower the calorific value, as observed by Livingston [17] and Loo and Koppejan [18]. Since 1% increase in ash content decreased calorific value by 0.2 MJ/kg [17], a high ash content in wood was an attribute of unsuitability for bio-thermal conversion process.

When converted into charcoal, *Prosopis africana* produced higher energy than *Burkea africana* [15], confirming the selection made on the wood

species. On comparison of values of moisture content, volatile matter, ash content, fixed carbon and calorific values of firewood species *Senna siamea*, *Anogeissus leiocarpus*, and *Khaya senegalensis* in Table 5 [12], with present data for B4, B8 and B10, indicated insignificant data differences, considering the ecological conditions and experimental errors.

3.4 Policy Implications

Identification of the most suitable wood species for bio-thermal conversion would reduce impact of anthropogenic activities on harnessing forest resources in Benin, and thereby reduce deforestation and environmental degradation, as well as mitigate against global warming. Carbonization of suitable wood species for charcoal production must yield high quality charcoal with higher calorific energy conversion efficiency. Identification of most suitable species for charcoal production would serve as management tool for charcoal production, in addition to total wood harvesting, selection of high demand species for reforestation programs and policies on wood fuel projects.

Experimental evaluation of quality of charcoal produced from the selected wood species, in conjunction data on growth, availability and nationwide distribution of the species would inform on citing of charcoal production facilities in Benin.

4. CONCLUSION

Not all wood species in Benin are suit-able for bio-thermal conversion by carbonization process.

Out of the ten wood species investigated, only *Burkea africana*, *Prosopis africana* and *Bridelia ferruginea* exhibited physico-chemical characteristics of high energy contents, high fixed carbon levels and relatively low proportions of ash and volatile materials, as required primarily for bio-thermal conversion.

Other secondary species identified as less suitable for charcoal production in Benin were *Khaya senegalensis*, *Anogeisus leiocarpa* and *Cassia siamea*. However, in addition to the criterion of physico-chemical properties, other variables, such as availability, geospatial distribution, and growth of the species, must be considered to set up total evaluation and selection criteria, so that other less suitable wood species could be used. The finding of the research constituted a decision-making tool for management of competition between wood fuel energy needs and industrial wood processing, in order to control environment degradation and deforestation.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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