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Characterization of Congolese Woody Biomass and Its Potential as a Bioenergy Source

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Abstract: This study assesses and characterizes six woody biomass (WB) species commonly harvested in the Republic of Congo: *Millettia laurentii* (WB1), *Millettia eetveldeana* (WB2), *Hymenocardia ulmoides* (WB3), *Markhamia tomentosa* (WB4), *Pentaclethra eetveldeana* (WB5), and *Hymenocardia acida* (WB6). Characterization was performed using proximate analysis with a Thermo Gravimetric Analyser (TGA), ultimate analysis with a CHNS Analyser, higher heating value (HHV) determination, metal content analysis by X-ray fluorescence (XRF), and aboveground biomass (AGB) estimation. The proximate analysis results showed that volatile matter varied between 74.6% and 77.3%, while the ultimate analysis indicated that carbon content ranged from 43% to 46%, with low nitrogen content. XRF analysis revealed low levels of heavy metals in all samples. The HHV results, using three models (Dulong's equation, Friedl, and proximate analysis), showed higher values with Friedl's method (17.3–18.2 MJ/kg) and proximate analysis (15.26–19.23 MJ/kg) compared to Dulong's equation (13.9–14.9 MJ/kg). Savannah biomass (WB6) exhibited high AGB (7.28 t), 14.55 t/ha, and carbon stock (7.28 t). Compared to forest biomass, savannah biomass presents a higher potential for bioenergy production. Minimal statistical analysis of wood biomass showed that parameters such as volatile matter (VM), carbon (C), hydrogen (H), and calculated HHV have low variability, suggesting the biomass is relatively homogeneous. However, moisture and nitrogen showed significant standard deviations, indicating variability in storage conditions or sample nature. Statistical analysis of forest biomass estimation revealed different mean values for diameter, AGB (t and t/ha), and carbon stock, with high standard deviations, indicating a heterogeneous forest with both young and mature trees. These analyses and estimates indicate that these WB species are suitable for biofuel and bioenergy production using gasification, pyrolysis, and combustion processes. Among these thermochemical processes, gasification is the most efficient compared to combustion and pyrolysis.

Keywords: bioenergy; proximate and ultimate analysis; lignocellulosic biomass; aboveground biomass; higher heating value

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1. Introduction

There is an increasing need to identify renewable energy resources in the form of materials, chemicals, fuels, and energy. Biomass is considered the most abundant and accessible renewable energy resource in most developing countries, contributing about 14% of the world's energy supply [1,2]. Woody biomass is particularly attractive for biofuel production because it does not create a "food versus fuel" conflict, unlike starch and vegetable oil-based feedstocks, which often divert agricultural land for fuel production [3]. Additionally, woody crops can be grown in agroforestry systems alongside food crops. These non-edible plant residues are also known as next-generation biofuel feedstocks or lignocellulosic biomass.

"Lignocellulosic" refers to raw materials containing cellulose, hemicellulose, and lignin in varying compositions. On average, lignocellulose makes up about 70% of plant cell walls and about half of the plant matter produced by photosynthesis, making it the most abundant renewable organic resource [4]. The annual global production of lignocellulosic biomass from terrestrial plants is about 17–20 $\times$ 10^{10} tonnes [5]. The Republic of Congo is largely covered by forest (80% of the national territory), representing 10% of all dense tropical rainforests [6]. This makes it a globally important carbon stock and a priority for biodiversity conservation. Lignocellulosic biomass includes agricultural and forestry residues and can be used as an energy feedstock. It can be converted into biofuels through three main routes: thermochemical, mechanical extraction, and biochemical processes.

Estimates of biomass potential are usually obtained by measuring aboveground biomass (AGB) using an allometric equation, which translates measurements such as diameter at breast height (DBH) and total height into volume and wood biomass [7].

Biomass characterization is crucial for evaluating suitable feedstocks for bioenergy production. Common tools used include ultimate analysis to determine the proportions of carbon, hydrogen, nitrogen, sulfur, and oxygen; proximate analysis to determine moisture content, volatile matter, fixed carbon, and ash content [2]; and X-ray fluorescence (XRF) spectroscopy to determine metal and mineral contents. Thermogravimetric analysis (TGA) is used to predict the thermal behavior of biomass during pyrolysis or combustion by determining the mass loss of the feedstock as a function of temperature under controlled heating rates and atmospheric conditions [8].

The physicochemical properties of lignocellulosic biomass have been extensively studied. Junmeng Cai et al. [9] reviewed properties such as particle size, grindability, density, flowability, moisture sorption, thermal properties, proximate analysis properties, elemental composition, energy content, chemical composition, and analytical characterization methods. They found that understanding these properties is key to designing effective thermochemical or biochemical processing methods, as they significantly influence process conversion performance.

Kalembkiewicz et al. [10] determined the chemical composition of lignocellulosic biomass in Abies religiosa wood across an altitudinal gradient using Van Soest gravimetric analysis and Fourier Transform Infrared (FTIR) spectroscopy. Their results showed cellulose content of 54.81 $\pm$ 2.20%, hemicellulose of 12.37 $\pm$ 1.33%, and insoluble lignin of 24.68 $\pm$ 1.16%. Musule et al. [11] studied forest biomass from chestnut coppice, maritime pine, poplar, and willow short rotation and found that biomass from maritime pine had a higher energetic value than poplar and willow clones and chestnut coppice, but also higher nitrogen and sulfur content. H. H. Haugen, N. C. I. Furuvik et al. [12] characterized biomass from wood chips of oak, birch, pine, and spruce to determine gasification and combustion properties. They concluded that moisture, calorific value, volatile content, and ash residue are the most important factors influencing these properties.

For sustainable bioenergy production, it is crucial to consider the availability and sustainability of potential biomass feedstock resources within a regional context. Potential woody biomass in the Congo region, such as WB1, WB2, WB3, WB4, WB5, and WB6, has not been previously characterized in the literature. These six species are abundant in tropical

Africa, so this analysis could have broader implications for identifying future feedstocks for bioenergy production in the region, particularly in the Republic of Congo.

The main objective of this research is to investigate the physicochemical composition of species abundant in the southern zone of Brazzaville, Republic of Congo. The study site is located in the village of Nguéla, Republic of Congo. Additionally, this study evaluates the potential of alternative biomass resources as suitable feedstocks for bioenergy production in the Congo region by assessing thermochemical conversion routes.

2. Materials and Methods

2.1. Biomass Harvesting

Woody plant biomass was collected in Nguéla village (04°22.273′ S 014°52.646′ E) from two square plots, each measuring 50 m × 50 m. These plots were further subdivided into eight smaller plots of 25 m × 25 m using a double decameter. In each plot, all woody specimens with a diameter at breast height (DBH, 1.30 m above ground) of 5 cm or more were counted. The DBH was determined by dividing the girth of each tree by π. Figure 1 illustrates the tree measurement process. The biomass samples were gathered from a secondary forest where the local population fells trees for agriculture or charcoal production. In this area, the population also plants maize, cassava, and vegetables.

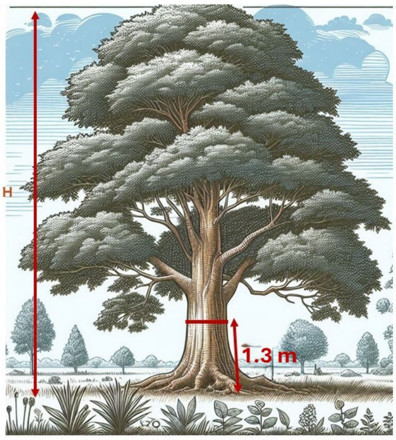

Figure 1. Illustration of the tree measurement.

The identified woody species were *Millettia laurentii* (WB1), *Millettia eetveldeana* (WB2), *Hymenocardia ulmoides* (WB3), *Markhamia tomentosa* (WB4), *Pentaclethra eetveldeana* (WB5), and *Hymenocardia acida* (WB6).

The collection process involved cutting the branches of the trees into smaller pieces, which were then placed in bags for pre-treatment such as drying and grinding. The samples were stored in plastic bags and cups for further analysis. These woody species have potential for agroforestry and energy production. The physical appearance of the woody biomass collected from each species is shown in Figure 2.

Figure 2. Pictures of (**a**) Millettia laurenttii (WB1), (**b**) Millettia eetveldeana (WB2), (**c**) Hymenocardia ulmoides (WB3), (**d**) Markhamia tomentosa (WB4), (**e**) Pentaclethra eetveldeana (WB5), and (**f**) Hymenocardia acida (WB6).

2.2. Assessment of the Biomass

We estimated the aboveground biomass (AGB) using the allometric equations as reported in Chave et al., 2014 [13], as described below:

$$AGBi = 0.067 \times (d_i \times (DBH_i)^2 \times H_i^{total})^{0.976} \quad (1)$$

where d_i is the wood density, DBH the diameter measured at breast height, and H_i^{total} the total height of the tree.

2.3. Biomass Characterization

Each biomass sample was dried for five days using a solar dryer and an oven. After drying, the samples were ground in two steps: first in a conventional blender, and then in a Retsch CryoMill (Retsch, Haan, Germany) to obtain a fine powder. The ground samples were sieved to achieve a particle size of less than 100 µm and stored in the dark until further characterization. Final ultimate, biochemical, proximate, HHV, and inorganic analyses were performed according to the protocol described by Tania et al. [14].

2.4. Ultimate Analysis

Ultimate analysis was carried out on all samples to determine the elemental composition of the samples. The samples were each analyzed for their carbon (C), hydrogen (H), nitrogen (N), and sulfur (S) content, with oxygen (O) calculated by difference, using Equation (2).

$$\boldsymbol{O\%} = \mathbf{100} - (\boldsymbol{\%C} + \boldsymbol{\%H} + \boldsymbol{\%N} + \boldsymbol{\%S}) \quad (2)$$

This was achieved using the CHNS Elemental Analyser Flash 2000, Thermo Fisher Scientific (Waltham, MA, USA) according to the protocols of Thermo Fisher Scientific [15]. The samples were weighed out to be approximately 3 mg and were crimped and sealed in tin capsules. These were then combusted in excess oxygen by the elemental analyser for measurement.

2.5. Calculation of the Higher Heating Value (HHV)

There are several models for estimating HHV from the final analysis of solid samples. Among these models, two models by Fiedl et al. [16] and Dulong's equation were considered. They gave an approximation for biomass fuels with an estimated standard error of ±337 kJ/kg, for which the predicted HHV (kJ/kg) was calculated from the final analysis in Equation (3). Values are presented on dry basis (db) with hydrogen corrected for moisture content.

$$\boldsymbol{HHV = 3.55C^2 - 232C - 2230H + 51.2C \times H + 131N + 20600} \quad (3)$$

Predicted HHV (MJ/kg) was calculated by ultimate analysis using Dulong's Equation (4) [17].

$$\boldsymbol{HHV\left(\frac{MJ}{kg}\right) = 0.3391 \times C(\%) + 1.444 \times H(\%) - 0.1805 \times O(\%) + 0.0942 \times S(\%)} \quad (4)$$

The estimation of HHV from proximate analysis (fixed carbon, volatile matter, moisture content, and ash content) [18] is provided using Equation (5).

$$\boldsymbol{HHV = 0.6042\ FC + 0.4083\ VM + 0.2442\ Ash + 0.4107\ MC - 25.204} \quad (5)$$

2.6. Proximate Analysis

Proximate analysis to measure the moisture, volatile matter, fixed carbon, and ash content of each sample was determined using a METTLER TOLEDO TGA/DSC 1 Thermo-Gravimetric Analyser (T.G.A.) (Columbus, OH, USA). A 10 mg sample of each biomass was first heated to 105 °C in an inert atmosphere at a rate of 10 °C min-1 and held isothermally for 9 min under an N2 atmosphere. The associated weight loss during this step represented the percentage moisture content. The sample was then heated to 900 °C—the weight loss during this stage determined the volatile content. The gas flowing through the analyser was switched from nitrogen to air to burn off the remaining fixed carbon. The ash content was measured as the material remaining after the test.

2.7. Inorganic Analysis

Inorganic analysis was performed using XRF spectroscopy (ZSX Primus II, Rigaku, Tokyo, Japan) with a 4.0 kW Rh anode (50 kV, 50 mA). The biomass samples were milled to less than 10 µm using a Retsch CryoMill with liquid nitrogen as a coolant for most samples. To produce the pressed pellets, 2.7 g of powdered sample was measured into a FluXana MU-S container, and 0.3 g of wax binder (BM-000261 CEREOX, Fluxana, Bedburg-Hau, Germany) was added. FluXana MU-MB-380-1 Polyamide 9 mm Mixing Balls were placed in the container, stirred with a small spatula, and the lid was secured. The containers were then mixed using the binder for 3–6 min. The sample-and-binder mix was sieved into a stainless-steel pressed pellet vial lined with a thin cellophane pellet film (PF-32-500, 32 mm diameter, FluXana) to prevent sticking.

Another pellet film was placed on top of the sample before the steel upper cylinder was inserted, and the vial was added to the press. The pressure was gradually increased to a maximum of 15 tons using a hand crank on the Specac instrument. Once the pressure gauge reached 15 tons, the pressure was released, and the steel vessel was carefully emptied. The samples, now in the form of small cylindrical pellets, were labeled accordingly.

The pellet samples were placed into metal pellet holders with screw-top steel lids and positioned in the Rigaku XRF ZSX Primus II instrument. The samples were analyzed in batches of 23.

2.8. Biochemical Analysis

Biochemical analysis was performed according to a modified Van Soest method [19]. The cellulose, hemicellulose, and lignin contents were determined. Neutral detergent fibre (NDF using amylase) was determined using the Gerhard Fibrecap system. Acid detergent fibre (ADF) was determined using the Gerhard Fibrecap system. Acid detergent lignin (ADL) was determined using a Fiber Analyzer System. The difference was used to calculate hemicellulose (NDF-ADF), cellulose (ADF-ADL), and ADL = lignin.

3. Results

3.1. Estimation of AboveGround Biomass (AGB)

Table 1 presents the estimated AGB forest biomass for various species inventoried in the Nguéla village area. The results indicate that species WB1, despite having a smaller diameter of 614.01 cm, possesses a high AGB value of 4.67 tC/ha and significant carbon stock. In contrast, species WB5, with a much larger diameter of 1854.6 cm, also shows high AGB values of 4.93 t, 9.85 t/ha, and 4.62 tC/ha. Although the AGB values for the first two species are slightly different, WB1 has a higher AGB value overall.

Table 1. Aboveground biomass (AGB) potential of forest biomass in t, t/ha and the carbon stock in tC/ha by the diameter of the species.

Species	Diameter (cm)	AGB (t)	AGB (t/ha)	Carbon Stock (tC/ha)
WB1	614.01	4.97	9.94	4.67
WB5	1854.6	4.93	9.85	4.62
WB3	1259.8	2.63	5.28	2.48
WB2	48.4	0.92	0.59	1.55
WB4	62.6	0.09	0.18	0.76

Compared to WB5 and WB3, which have very large diameters, WB1 has a much smaller diameter. However, WB1 shows a high AGB and contains more carbon than both WB5 and WB3. Additionally, while WB2 and WB4 have smaller diameters, WB2 has a slightly larger diameter, higher AGB, and greater carbon content than WB4.

Table 2 shows the estimated savannah biomass calculated in t, t/ha, and the carbon stock calculated in tC/ha of the species. The result shows a very high diameter value (645.28 cm) of the WB6 and has a very high potential in AGB (7.28t), (14.55 t/ha), a high (14.55 t/ha) and a high carbon stock (6.84 tC/ha). The values of our study are lower than the value reported by [20].

Table 2. Aboveground biomass (AGB) potential of savannah biomass in t, t/ha and the carbon stock in tC/ha and the diameter (cm) of the species.

Species	Diameter (cm)	AGB (t)	AGB (t/ha)	Carbon Stock (tC/ha)
WB6	645.3	7.28	14.55	6.84

Table 3 presents the statistical analysis conducted on the woody biomass (WB). First, the mean diameter is relatively high, but the large standard deviation (784.49 cm) indicates a wide variation in tree sizes. The minimum and maximum values reveal a heterogeneous forest, with young trees having a diameter of 48.4 cm and very mature trees reaching up to 1854.6 cm. This variability is typical in natural or old-growth forests where trees of different sizes coexist.

Table 3. A statistical analysis of the estimation for the forestry biomass.

Parameters	Mean	Maximum	Minimum
Diameter (cm)	767.882 ± 784.489	1854.6	48.4
AGB (t)	2.708 ± 2.24226	4.97	0.09
AGB (t/ha)	5.168 ± 4.75773	9.94	0.18
Carbon stock (tC/ha)	2.816 ± 1.77725	4.67	0.76

The find of the mean aboveground biomass of a tree is 2.708 tonnes, but the large standard deviation (2.24226 tonnes) indicates significant variability. Some trees have very low biomass (young trees or small species), while others reach almost 5 tonnes. This uneven distribution of biomass is typical of diversified ecosystems.

Aboveground biomass per hectare also varies widely, with a mean of 5.168 t/ha and a standard deviation almost as high as the mean. Low values (0.18 t/ha) could correspond to recently degraded, deforested, or sparsely wooded plots, while high values (up to 9.94 t/ha) are typical of dense, well-developed plots.

The mean carbon stock is 2.816 tC/ha, indicating that, on average, each hectare of forest contains about 2.8 tonnes of carbon. The moderate standard deviation (1.77725 tC/ha) shows some variability in the carbon storage capacity of forest plots. Low values (0.76 tC/ha) are associated with degraded areas or young forests, while high values (4.67 tC/ha) reflect more mature areas with high density and large, well-developed trees.

3.2. Proximate Analysis, Ultimate Analysis, and HHV

The proximate analysis, ultimate analysis, and HHV of the biomass samples are presented in Table 4.

Table 4. Proximate analysis, ultimate analysis, and HHV of the woody biomasses.

Analysis	WB1	WB2	WB3	WB4	WB5	WB6
Volatile Matter (%db)	77	77.2	75.6	77.3	76.1	74.58
Fixed Carbon (%db)	12.4	11.4	12.7	12	12.8	14.63
Moisture (%db)	13.4	7.2	4.7	5.5	7.9	8.53
Ash (%db)	-	-	-	-	3.1	ND
C (%db)	43.5	44.4	45.4	44.0	43.4	45.85
H (%db)	6.1	5.9	5.5	5.9	5.7	5.61
N (%db)	1.3	0.8	0.5	1.1	0.7	0.66
O (%db)	49.1	48.9	48.6	48.2	50.2	48.03
HHV (MJ/kg) db (Dulong)	14.7	14.7	14.6	14.7	13.9	14.9
HHV (MJ/kg) db (f ° (Proximate analysis))	19.23	16.16	15.26	15.86	16.84	17.58
HHV (MJ/kg) db (Friedl)	17.4	17.7	18.0	17.5	17.3	18.2

db = dry basis. ND = not determined. HHV = higher heating value.

The results indicate that WB3 has a higher carbon content than the other four woody species. The nitrogen content varied between 0.5% and 1.3%. The calorific value of the biomass is also correlated with its ash content. The results of ultimate analysis of these biomasses are similar to [21].

The amounts of fixed carbon and volatile matter (VM) are important for fuel production through thermochemical conversion, as they provide insight into ignition and gasification properties [2]. Biomass with higher VM is more reactive and produces less char during pyrolysis [2]. WB4 samples contain higher VM, whereas WB3 has lower VM content. The fixed carbon content also varied, with values of 11.4% and 12.8%.

In summary, ultimate, proximate, and higher heating value (HHV) analyses show good agreement for the composition of all samples collected. The values of carbon, nitrogen, hydrogen, oxygen, and sulfur for different WB species align with results available in the literature [20,22].

The HHV results using Dulong's equation range from 13.9 to 14.9 MJ/kg, which are relatively low. In contrast, HHV results from proximate analysis range from 15.26 to 19.23 MJ/kg, which are higher. Proximate analysis is a better method than Dulong's equation for estimating HHV.

We found that the Friedl model is the best method for estimating HHV because it provides higher values, indicating greater energy production. The HHVs in this study are lower than those found by [15], but these results are not consistent with the literature [16].

The final analysis of all wood biomass results was similar to those reported in the literature by [20]. These values are in agreement with those reported by [18,23]. The final analysis of all wood biomass results was similar in the same range as reported in the literature by [24]. These values are in agreement with those reported by [25].

Table 5 provides a clear statistical analysis of the proximate and ultimate analyses, as well as the higher heating value (HHV) of the WB. A high proportion of volatile matter indicates the biomass is rich in compounds that release combustible gases at high temperatures, with a low standard deviation (1.08) suggesting homogeneity. Low moisture content is beneficial for energy applications, though the high standard deviation (3.07) indicates significant variability, possibly due to different sources or storage conditions. Fixed carbon, representing the residual fraction after volatile release, is moderate, with a standard deviation (1.09) indicating some variability. Carbon content significantly contributes to heat energy, and a low standard deviation shows good homogeneity. Hydrogen content, which improves combustion quality, shows low variability. A low nitrogen percentage is favorable for limiting NOx emissions, though the variability is high. High oxygen content, typical for biomass, decreases energy density but shows good sample homogeneity, corroborating results reported by [26]. The HHV using the Dulong method shows a mean value of MJ/kg $\pm$ 0.35, based on elemental composition, with low variability, indicating reliable results. The HHV using the Friedl method (17.76 MJ/kg $\pm$ 0.34) offers slightly higher values due to an empirical approach specific to biomass, showing good consistency between samples. The HHV from proximate analysis shows a mean value of 16.83 MJ/kg $\pm$ 1.43, with the greatest variability, indicating that the heating value strongly depends on the proportions of fixed carbon and volatile matter, corroborating results reported by [26]. Parameters such as volatile matter, carbon (C), hydrogen (H), and calculated HHV show low variability, suggesting the biomass is relatively homogeneous. Moisture and nitrogen show significant standard deviations, indicating variability in storage conditions or sample nature. These biomasses, with average HHVs ranging from 14.58 to 17.76 MJ/kg, are well-suited for thermochemical applications (combustion, gasification, and pyrolysis), although moisture management remains a key issue.

Table 5. A statistical analysis of the proximate analysis, ultimate analysis, and the HHV for wood biomass.

Parameters	Mean	Maximum	Minimum
	Wood Biomass		
Volatile Matter (%db)	76.29667 ± 1.07595	77.3	74.58
Moisture (%db)	7.87167 ± 3.07025	77.3	74.58
Fixed Carbon (%db)	12.655 ± 1.09478	14.63	11.4
C (%db)	44.425 ± 1.00685	45.85	43.4
H (%db)	5.785 ± 0.22125	6.1	5.5
N (%db)	0.84333 ± 0.29944	1.3	0.5
O (%db)	48.83833 ± 0.78027	50.2	48.03
HHV (MJ/kg) db (Dulong)	14.58333 ± 0.34881	14.9	13.9
HHV (MJ/kg) db (Friedl)	17.76 ± 0.33615	18.2	17.4
HHV (Proximate analysis)	16.825 ± 1.42776	19.23	15.26

3.3. Biochemical Compositional

Biochemical analysis using the Van Soest method provides information on cellulose and lignin content. Table 6 summarizes the biochemical analysis results of WB. The cellulose content in WB ranges from 17.47% to 32.55%, which is higher than the hemicellulose content, ranging from 11.01% to 23.39%. These values align with those reported by [22]. However, WB has a relatively low lignin content. The biochemical composition results obtained in this study are similar to those reported in the literature [2,27].

Table 6. Biochemical analysis of woody biomass.

Analysis	WB1	WB2	WB3	WB4	WB5	WB6
Hemicellulose (%)	11.01	14.8	20.7	13.1	23.4	12.44
Cellulose (%)	17.0	18.7	17.5	27.1	32.6	31.5
Lignin (%)	7.5	12.9	12.0	7.3	18.5	18.48

The decomposition steps of biomass during thermochemical conversion depend on its biochemical composition. For example, pyrolysis decomposes hemicellulose, cellulose, and lignin at temperatures ranging from 220–315 °C, 315–400 °C, and 500–900 °C, respectively [2]. Pyrolysis of cellulose and hemicellulose produces a higher bio-oil yield than lignin, which significantly contributes to the formation of residual char. Generally, higher nitrogen content makes the feedstock less suitable for solid fuel and bio-oil production.

Proximate analysis results showed that the moisture content in WB1, WB2, WB3, WB4, and WB5 ranged from 4.7% to 13.4%, consistent with the literature [8,9]. Higher moisture content in biomass requires more heat during thermochemical processes to remove the moisture. The levels of fixed carbon (FC) and volatile matter (VM) are crucial for determining the ignition and subsequent gasification/oxidation characteristics of biomass, depending on its use as an energy source [2]. The volatile matter content of the WB samples ranged from 74.6% to 77.3%.

Higher ash content in biomass proportionally reduces the energy content of the fuel. During thermochemical conversion, the chemical composition of the ash can lead to operational problems, particularly in combustion processes where ash can form slag at higher temperatures. The results of this study showed that the ash content in the wood biomass was low and comparable with [28,29].

Table 7 provides a clear statistical analysis of the biochemical analysis of the WB. Hemicellulose showed a mean value of 15.91% ± 4.98%; we observed that the values (11% to 23%) are typical for woody biomasses, where hemicellulose generally represents 15% to 35% of the wood depending on the species. The low proportion relative to cellulose reflects the secondary structural nature of hemicellulose in cell walls. Our results corroborate results reported by [26].

Table 7. A statistical analysis of the biochemical analysis of the wood biomass.

Parameters	**Mean**	**Maximum**	**Minimum**
	Wood Biomass		
Hemicellulose (%)	15.90833 ± 4.98444	23.4	11.01
Cellulose (%)	24.06667 ± 7.19907	32.6	17
Lignin (%)	12.78 ± 4.97474	18.5	7.3

Mean values of cellulose are represented (24.07% ± 7.20%). The cellulose contributes to rigidity and plays a key role in bioenergy applications and in the production of biomaterials. These values (17% to 32.6%) are slightly lower than the generally expected averages for cellulose in forest wood, which are often between 40% and 50%. This could indicate a higher proportion of other components (such as lignin) or the specific nature of the sample analyzed. These results are similar to those reported by [26,30].

The cellulose observed here is lower than the expected average, which could reflect young wood or a partial extraction method.

The observed lignin values (7.3% to 18.5%) are within the typical range for woody biomasses. A moderate to high lignin content is favorable for applications such as pyrolysis or biochar production. However, a high proportion can complicate biochemical conversion processes such as fermentation. Lignin in this sample is lower than these averages, which may reflect young or low-density wood. These results are similar to those reported by [26,30].

The average proportions show moderate cellulose and lignin content, with a relatively low proportion of hemicellulose. These characteristics are typical of low-density or softwood (resinous) woods.

3.4. Inorganic Composition

The woody biomasses were analyzed by XRF and the results are presented in Table 8. The results of the wood biomass showed more macro-elements such as Mg, Al, Si, P, S, K, Ca, Ti, Mn, and Cl and fewer elements such as Fe, Cu, Zn, Rb, Sr, Na, Cl, Re, and Ga. These results are similar to those reported in the literature [31].

Table 8. XRF analysis results for woody biomass.

Elements (ppm)	**WB1**	**WB2**	**WB3**	**WB4**	**WB5**	**WB6**
Mg	535	547	286	676	450	774
Al	42	57	64	85	35	35
Si	848	335	89	746	112	819
P	1189	705	570	407	786	949
S	653	557	296	1167	591	336
K	1551	1676	888	1281	1371	2221

Table 8. *Cont.*

Elements (ppm)	WB1	WB2	WB3	WB4	WB5	WB6
Ca	1189	1145	862	2051	1639	1771
Ti	148	/	135	106	103	ND
Mn	36	28	21	33	/	29
Fe	27	31	16	43	48	26
Cl	/	71	109	52	104	182

3.5. Economic Analysis Based on the Price and Energy Density of the Forest and Savannah Biomass Fuels

Forest and savannah biomass are readily available in Nguéla village and hold significant potential for bioenergy production. Conducting an economic analysis based on biomass pricing is crucial. The estimated delivery cost of forest and savannah biomass for energy production depends on the processes of harvesting, handling, transportation, and storage. To minimize these costs, the harvested biomass will be dried and ground on-site to produce pellets for energy production. This approach aims to reduce transportation and storage costs while enhancing energy production efficiency. Pellets are particularly suitable for bioenergy production due to their high energy density, which refers to the amount of energy delivered per unit of mass or volume of fuel, measured in kWh/kg.

Savannah biomass from 1 hectare produces 14.56 tons of biomass, supplying 218.4 GJ of energy. In terms of energy density, 14.56 tons of biomass provide 4.16 kWh/kg. Consequently, 1/2 hectare, yielding 7.28 tons, delivers 2.0833 kWh/kg.

4. Discussion

In this study, we assessed the potential of six types of woody biomass for bioenergy production and characterized these biomasses. We demonstrated that using wood biomass for bioenergy does not negatively impact the environment, such as causing deforestation. Additionally, we estimated the amount of electricity that can be generated from this wood biomass.

This species thrives in evergreen forests, especially on the edges, as well as in gallery forests, rainforests, dry forests, wooded savannahs, fallow land, and grasslands with trees. It can also be found on termite mounds and in "chipya" woodland on rocky ground, typically at altitudes of 100 to 1000 m. Considering the ecology of these woody biomasses, they could be grown alongside agricultural crops such as cassava and beans in agroforestry systems.

However, not all biomass energy solutions are equal. Some environmental disadvantages of bioenergy can be mitigated through sustainable forest management, as mentioned by Brian D. Titus et al. [31], and wise choices about what kind of biomass is harvested and how it is harvested. Lauri et al. [32] recommend using branches and stumps rather than cutting down whole trees for bioenergy production. Eirik Ogner Jåstad et al. [33] concluded that woody biomass significantly contributes to reducing fossil emissions in heat and power generation in Northern Europe. Excluding biomass from heat and power generation could lead to higher costs during the transition to a low-carbon energy system.

The Republic of Congo has a large forest area with many forest residues that have not been properly exploited. Estimating the biomass potential is crucial before biofuel and bioenergy production. Charcoal use in the Republic of Congo is high and leads to deforestation of the Congo Basin. The quantities of woody biomass such as WB1, WB2, WB3, WB4, WB5, and WB6 are abundant and can provide a sustainable energy source for rural communities, especially in Nguéla village. These woody biomasses are not widely used for food and their availability has not been well reported.

Our results showed high levels of aboveground biomass (AGB) in WB6, WB1, WB3, and WB5. By quantifying the biomass of five forest species and savannah species over half a hectare, we estimated 13.54 t for forest species over 1/2 ha. Extrapolating to one hectare, we found 27.08 t for forest biomass. This amount of forest biomass (13.54 t) can produce 203.1 GJ for 1/2 ha and 406.2 GJ for 1 ha.

The Republic of Congo's total electrical energy consumption is 912.00 million kWh [34], corresponding to an annual consumption of about 161 kWh per inhabitant, equivalent to 0.5796 GJ. Therefore, 1/2 ha of forest biomass (203.1 GJ) could potentially produce enough electricity for 350 households, while 1 ha (406.2 GJ) could supply 700 households. For savannah biomass, 1/2 ha (109.2 GJ) can supply 191.6 households, and 1 ha (218.4 GJ) can supply 376.81 households.

In terms of physico-chemical analysis, all woody biomasses have low nitrogen and sulfur content and fewer heavy metals, making them unsuitable for anaerobic digestion but suitable for thermochemical processes such as pyrolysis and gasification for bioenergy production. The HHV of woody biomasses indicates that the energy content of the samples is relatively low. The statistical analysis showed that these wood biomasses are suitable for thermochemical processes, particularly gasification, with results similar to [30].

5. Conclusions

We have estimated and characterized six woody biomass (WB) species. WB1, WB3, WB6, and WB5 were identified as the dominant species with high aboveground biomass (AGB) and significant carbon stock.

X-ray fluorescence analysis revealed high levels of macro-elements and low levels of heavy metals in the wood biomass. The characterization results indicate that the low nitrogen and sulfur content makes these wood biomasses suitable for biofuel or bioenergy production through thermochemical processes such as gasification, pyrolysis, and combustion. These species show good potential for biofuel or bioenergy production and can be integrated with other crops in agroforestry systems.

To minimize environmental impacts like deforestation, it is recommended to use only branches and stumps for bioenergy production. To maintain environmental sustainability and enhance the efficiency of biofuel and bioenergy production, it would be beneficial to plant trees on a large scale and utilize various raw materials, including forest residues, agricultural residues, and industrial residues.

Minimal statistical analysis of the wood biomass revealed low variability in parameters such as volatile matter, carbon (C), hydrogen (H), and calculated HHV, indicating a relatively homogeneous composition. However, moisture and nitrogen exhibited significant standard deviations, reflecting variability in storage conditions or sample characteristics. With an average HHV ranging from 14.58 to 17.76 MJ/kg, this biomass is highly suitable for thermochemical processes, including combustion, gasification, and pyrolysis.

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